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Written By	Filip Neele (TNO), Florence Delprat-Jannaud (IFPEN), Oliver Vincké (IFPEN), Valentina Volpi (OGS), Manuel Nepveu (TNO), Cor Hofstee (TNO), Jens Wollenweber (TNO), Ane Lothe (SINTEF), Susanne Brunsting (ECN), Jonathan Pearce (BGS), Anne Battani (IFPEN), Axelle Baroni (IFPEN), Bruno Garcia (IFPEN), Maxine Akhurst (BGS)	
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Executive summary

Carbon Capture and Storage (CCS) is one of the solutions that can significantly reduce CO_2 during the transition from fossil fuel-based energy to an energy system based on renewable energy sources. One of the requirements for the successful and timely development of CCS is the availability of qualified storage space. The aim of the EU FP7 SiteChar project was to develop an efficient site characterisation workflow, to support the development of the numerous storage sites that will be needed for large-scale deployment of CCS. This report presents a workflow for the characterisation of a site for the geological storage of CO_2. The workflow is designed to address all aspects of secure and permanent storage required by the EU Storage Directive. The links between the Storage Directive requirements and the work done and results obtained in a site characterisation are described in detail. The workflow describes the elements of a site characterisation study (such as building a model of the subsurface geology, modelling the behaviour of the injected CO_2, analysing the impact of injected CO_2 on subsurface faults). Special attention is paid to the links between the different disciplines that together form the multidisciplinary site characterisation team.

Five potential CO_2 storage sites were studied in the SiteChar project; the work in these sites was used to test and improve the workflow. The key points in a characterisation and assessment study are the following.

1. A site characterisation study for CO_2 storage intends to fulfil the regulatory obligations, such as those laid down in the EU Storage Directive. Two parties are directly involved: the operator of the prospective site and the so-called Competent Authorities. *It is necessary that the parties have regular contact.* These contacts will inform the operator on what is expected from him in the study, on the basis of the national implementation of the EU Storage Directive. They must also lead to a fuller understanding of the prospective site by the CA, who is 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 involved defines risks and associated adverse scenarios and the work should always be based on the risk assessment and risk ranking. Here again the informal contacts with the CA are a practical necessity. The detailed site characterisation, numerical in nature, may uncover new risks that were not anticipated earlier. These risks must lead to reiteration. It is advisable that parties involved agree on a protocol to be followed in such cases.
3. A site characterisation study is *multi-disciplinary*. The activities in each discipline are described in this report, with special emphasis on the links between the disciplines. It must be stressed that the focus of the activities in each discipline are strongly *site specific*.
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.* These plans are also *risk-based* and *site-specific.*

The prime keywords in site characterisation are "**risk-based**" and "**site-specific**". The current document maps out a general route in a site characterisation study, but certainly does not describe a process that can be routinely followed. In order to speed up the process of site characterisation and assessment the workflow presented in this report can help focus the work

and build awareness of the issues mentioned above. Many sites have to be scrutinized within the coming decade in order to ensure timely implementation of CCS on a European scale.

1 Introduction

The large-scale introduction of Carbon Capture and Storage (CCS) in 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 formations is largely sufficient to store CO_2 emission for several decades into the future (IEA, 2013), but the larger part of this capacity remains unproven, which places it in the lowest 'theoretical' level of the CSLF storage pyramid (Bachu *et al.*, 2007; Vangkilde-Pedersen *et al.*, 2009). Over the past years, the introduction of CCS has developed at a slower pace than required if emission reduction targets are to be met. One of the key actions to be taken is pre-competitive storage assessment (IEA, 2013), to remedy the absence of a sufficient volume of proven storage capacity. Storage capacity is available in depleted gas and oil fields and in deep saline formations. The latter represents the largest, but least characterised, storage capacity. 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.

The development of a storage site, which includes exploration, characterisation and infrastructure development, for CCS is a time-consuming and costly process. While the development and building of a capture plant is the most capital intensive part of a CCS project, 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.

One of the central goals within the SiteChar project is to develop a workflow for site characterisation studies for the storage of CO_2 under the EU Storage Directive. The workflow presented in this report defines the work to be done to comply with the EU Storage Directive (EU, 2009), resulting in efficient site characterisation studies. The workflow was applied on five potential storage sites; the experience thus acquired forms an integral part of the report.

This document is intended as a guide to site characterisation. However, it is not a "cook book" in the sense that it must be duly followed in all and every respect. The potential sites are "individuals" with their particular properties. One has to acknowledge that and act accordingly in the workflow.

1.1 Workflow background

Several studies have been completed that address site characterisation for geological CO_2 storage (SAMCARDS 2003; CO2CRC, 2008; WRI, 2008; DNV, 2009; NETL, 2010; Neele *et al.*, 2011). The studies describe, to varying degree, the work to be done to include all aspects relevant to 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 efforts to streamline the development of CO_2 storage sites and the development of CCS in general, standards for the storage of CO_2 have been published, in Canada by the CSA (CSA, 2012) and in Europe by DNV (DNV, 2012). Both standards cover the complete lifetime of a storage project, from screening until and including closure. The present document can be used alongside either of the two standards, as the work to be done in site screening and site characterisation is the same, at least strongly similar, in different regulatory environments. Regulatory differences will become apparent in the details of the permitting process.

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. Awareness of these steps helps avoid unnecessary delays.
- Interdependencies and feedback loops within the process. The activities in a site characterisation study are strongly interlinked, creating an iterative process. A description of the links will result in awareness in the multidisciplinary characterisation team and improve the flow of results and information.
- The coverage of the different requirements of the EU Storage Directive in the process. The EU Storage Directive (EU, 2009) 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 how to address the EU Storage Directive aspects with results obtained in a site characterisation study.

This reports aims to provide support to site characterisation teams in all three areas.

1.2 Three focal points

Three issues play a significant role within the workflow: the interplay between the operator and the competent authorities, interdependencies and feedback loops within the site characterisation team and, finally, the risk analysis that is at the heart of a site characterisation.

Interplay 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” (henceforth CA) as mentioned in the EU Storage Directive. 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 it is clear who they are in any concrete situation. In a formal document like the EU Storage Directive the CA feature at formal moments in the process that may lead to CO_2 storage. The guidance documents on “Implementation of Directive 2009/31/EC on the geological storage of carbon dioxide” (EU, 2011) are a much welcomed addition in that they advise the CA on how to perform their tasks at such moments, or rather, what issues should have their full attention. *From a practical point of view it has become increasingly clear that the contacts between the operator and the CA cannot remain restricted to formal moments in time*. Chapter 4 discusses this issue.

Interdependencies and feedback loops
Describing a workflow might be relatively easy if it were a linear process. Indeed, the starting point and the endpoint are clear enough. At some point a site or a series of sites are looked upon as potential candidates for CO_2 storage, and in the end one or more concrete sites are chosen, deemed apt for storage, and storage permits being requested from the authorities.
Strict and straightforward linearity is an illusion, especially when the various geo-scientific disciplines are invoked in the quantitative aspects. For example, quite possibly new data or new data studies from geochemists, for instance, will induce the geologists to change the 3D static earth model, which then may have consequences for the reservoir engineer studying the fluid dynamic properties of the potential storage strata. Furthermore, the results obtained by the reservoir engineer may induce further questions for the geologist, leading again to adaptations. It is hard to tell in advance where these feedback loops will turn up in any concrete investigation, but it is important to be aware of the possibility and to stay alert. Chapter 4 on discusses these issues.

Risks-based workflow and site specificity

Qualitative Risk Assessment is the genuine driver for the characterisation process. It is the process of identifying risks / scenarios that might be adverse to human safety and the environment.

The risks as perceived by a team of disciplinary experts guide the work to be done. This perception is at first qualitative, based on general and site-specific knowledge concerning features, events and processes that may or may not play a role. Qualitative Risk Assessment is the starting point of the characterisation and assessment after a Screening Phase. Even at the very beginning of the Screening Phase this assessment plays some role. It is even stronger: the qualitative Risk Assessment accompanies the process all along. If new, unexpected aspects turn up in the course of the quantitative work it will play an important role, as it is part of a feedback loop. It interacts with quantitative work all along. *The qualitative and quantitative aspects of risk assessment are intertwined.*

1.3 Reading guide

The report is built up as follows:

- Chapter 2 presents a general overview of the risk assessment workflow. Emphasis is put on characteristics and drivers of this process.
- Chapter 3 describes the screening study, at the very beginning of the process.
- Chapter 4 discusses communication issues. This topic is non-technical but plays a significant role in the success of the assessment process.
- Chapter 5 is dedicated to the regulatory context that forms the legal basis for all characterisation and assessment activities.
- Chapter 6 describes the qualitative risk assessment with its input and expected output.
- Chapter 7 describes the different scientific disciplines that play a role in the process, especially for the quantitative site characterisation. The ties of these disciplines with each other are explicitly borne out.
- Chapter 8 describes the monitoring and mitigation (corrective measures) plans. These form input for the site development plan and economics, also treated in this chapter.
- Chapter 9 gives concluding remarks.

2 WORKFLOW IN HELICOPTER VIEW

2.1 Workflow elements

A site characterisation study generally commences with a screening and selection study of potential sites, in which the options for storage in a given area or region are investigated. The workflow presented here combines the (high-level) screening study with a (detailed) site characterisation study. The workflow is graphically presented in Figure 2.1. The arrows in the figure represent the flow of the work activities and of information. The figure contains a number of iterations (feedback loops, shown in the figure through arrows that point back towards an ‘earlier’ stage in the general flow of work and information) and decision points (diamonds).

It is important to emphasize that a site characterisation study is multidisciplinary. In the remainder of this report it is assumed that the study is performed by a team of experts, who work closely together and exchange data and results. This is similar to the situation 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 sideburdens. In the case of CO_2 storage the ability of a geological structure to trap and retain CO_2 permanently must be demonstrated, whereas in oil and gas exploration the object of study is a proven reservoir. In fact, 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 programs can be conducted. If the risks fall below an a priori defined threshold, the site can be used for storage. The areas of expertise that must be covered by the team include:

- Geophysics / structural geology / sedimentology / petrophysics
- Reservoir engineering,
- Geomechanical modelling,
- Geochemical analysis and geochemical modelling,
- Well engineering,
- Risk assessment,
- Social analysis.

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

- Economic analysis,
- Engineering and design of injection facilities.

The workflow can be separated into two main elements, screening and characterisation, and a number of sub-elements, indicated in Figure 2.1. These elements are indicated briefly below and described in more detail in the chapters indicated.

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 CAs 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), economic considerations (distance from the capture plant, cost of storage, other uses of the pore space). Risk assessment 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. Other aspects should also be included at this stage, such as environmental and societal restrictions. In this phase, no new data is collected. Experts will use knowledge of a general nature to form an opinion on available data. Overall geo-scientific knowledge of the region is an important part of the input and the decision-making. Meanwhile, some general rules of thumb are available that make the preliminary estimates somewhat easier (see, *e.g.*, Ramirez *et al.* (2010) for a review in this respect). The expected output of the screening phase is a shortlist of promising potential storage sites. It is worthwhile emphasizing that at this stage storage sites can at best be deemed promising. The next step, characterisation and assessment, is meant to either elevate such sites to the status of “suitable”, or dismiss them. Chapter 2.5 describes the screening phase.

2. *Site characterisation study* (including assessment). Any promising site on the shortlist is eligible for the next step of ”characterisation”.

    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 no shortage of existing data. Well data, production data and reservoir models may be available. For saline formations, the situation might be 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, 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 data collected is sufficient to give potential evidence of the storage prospect. The available data may come from companies, which collected the data for an entirely different goal. For instance, oil companies are mostly not interested in the mechanical properties of the seal, whereas this aspect is of paramount importance for the final assessment of the site’s suitability as a CO_2 storage site. Hence, the CA should view the data with respect to their completeness for the characterisation and assessment as intended*.* Chapter 4 on Communication issues treats this.

    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. In practice, the persons covering the areas of expertise listed on page 9 consider all the available data, so as to find anything that could impede secure and permanent storage, or that could affect the site’s ability to meet the storage requirements (as described under 1) ‘screening study’). Section 6.2 is devoted to this.

    c. A qualitative Risk Assessment (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 security and permanency of storage, as well as the conformity to storage requirements. The aim of this step in the workflow is to identify whether there are aspects that render storage at the site (economically) unviable, and whether additional data is to be collected. Risks associated with the site have to be listed and described in detail in the remainder of the characterisation study. Section 6.3 is devoted to qualitative RA.

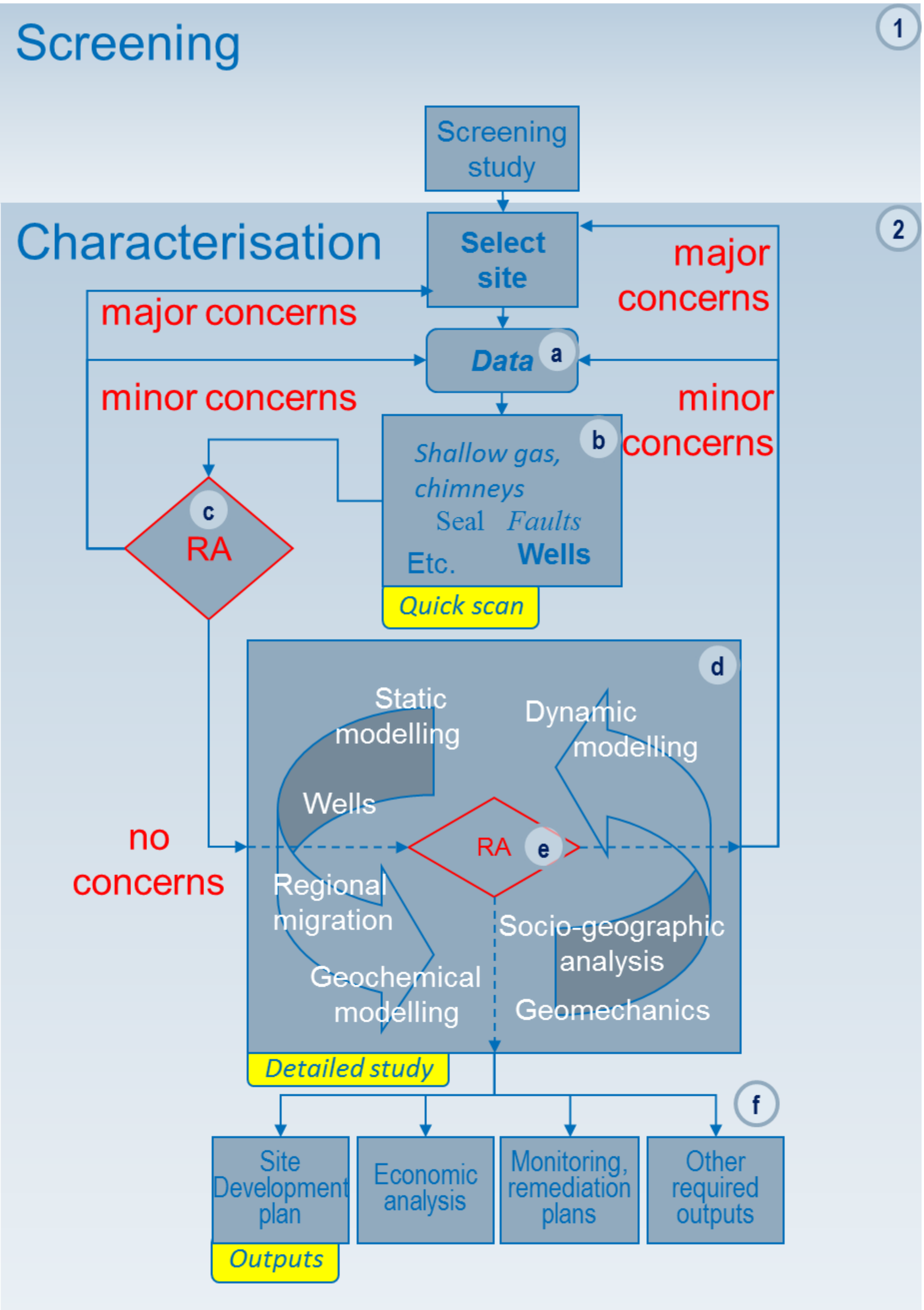

Figure 2.1 Workflow of site screening and characterisation. The numbers in circles refer to the list in chapter 2.

d. When the qualitative risk assessment is passed, the site is studied and modelled in the different areas of expertise. This is represented by the large box labelled 'Detailed study' in Figure 2.1. 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. In this phase the risk assessment is present all along. Chapter 7 is devoted to the quantitative / analytical aspects of RA and characterisation.

e. Once all aspects of secure storage have been studied and once internal consistency in results and data is reached, the risk analysis can be made quantitative, *i.e.* Health, Safety and Environment (HSE) analysis can be performed. Risks are compared to a priori determined risk threshold(s). 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. In this report 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. If HSE analysis shows that risk thresholds are exceeded, then the site is to be discarded.

f. When the risks fall below established threshold(s), *e.g.* because there is an option of monitoring and mitigation, the last elements of a site characterisation study discussed here 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. 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, and not formally required by the Storage Directive. The analysis of the cost of storage is not possible without a detailed site development plan. At the same time, economic analysis influences the site development plan. Chapter 8 is devoted to monitoring plans, corrective measures plans, the development plan and cost analysis.

2.2 Risk-based, site-specific action

An all-important consideration in the characterisation and assessment study is that it is *risk based* as well as *site specific,* as mentioned in the previous chapter,. The qualitative risk assessment will act as a guideline that pervades the study in all respects. The scenarios that may lead to significant irregularities and are quite possible in the given, site-specific situation have to be investigated in detail. Obviously then, the qualitative phase for risk assessment is of overriding importance. The team must be such that "sensible completeness" can be reached. The work of the team of experts must yield a so-called *risk register*. The risks in the register are plotted in a risk matrix. This is a diagram in which risks are positioned along two axes: probability vs. severity. This is a graphic method that indicates which risks have to be scrutinized in full measure. This risk register and risk matrix will guide subsequent numerical work.

After this phase has been completed it should also be clear what level of detail of scrutiny is desirable, and which theories and approximations of the different parts of the investigation are deemed appropriate to reduce the uncertainties to acceptable levels. During the following phases, 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 as the processes unfold. *If and when such new risks arise in the risk assessment and characterisation process has to be reiterated*. From a practical stance it might be appropriate to formalize the process and appoint persons whose task it is to make sure that new risks are brought into the process, if appropriate. For obvious reasons the CA should be informed with each major "discovery". In any case the CA and the operator should decide what has to be done, so as to smooth the process, and avoid unwelcomed delays at the formal moments in the storage permitting process.

2.3 Basic considerations on risk assessment

Before a risk assessment can take place, the assessment basis must be defined, *i.e.* what type(s) of risks are actually assessed? For site characterisation purposes the overriding goal is to assess whether injected CO_2 is likely to remain stored and if leakage occurs, whether this might have consequences for Health, Safety and Environment (HSE). [Note that in all kinds of "official" documents risk assessment in connection with CO_2 storage is always interpreted on the basis of HSE. However, for a site operator, economic risk is important and a risk assessment on this basis as well as on HSE issues may be undertaken. This aspect is usually treated somewhat differently, by financial-economic specialists.]

All risk assessments start with risk identification and qualitative evaluation. This is a crucial phase that should preferably be performed very early in the process of site characterisation and assessment, even before collection of site data starts. Such a mode of behaviour is prudent: in this way the whole process will be better focused. The main risks that can be defined a priori might include:

- CO_2 leakage via the seal rock, fault or well or laterally via a spill point, possibly leading to impact on humans, animals and vegetation or to degradation of water quality;
- Brine displacement possibly leading to degradation of the quality of fresh groundwater;
- Ground movement, either seismic or a-seismic possibly leading to damage of infrastructure.

The following information sources should be used where available:

- Existing databases with risk factors (*e.g.* FEP databases, F=Features, E=Events, P=Processes);
- Previous site behaviour
- Expert elicitation.

The selection of experts should be such that all involved disciplines are well covered. Expert judgment is used in identifying which risks and technical issues are relevant and which are of less importance. The expert team should include those who are knowledgeable on site-specific aspects. It is important to note that co-operation of several experts with different backgrounds will help to counteract tunnel vision and is the best remedy against overlooking significant effects. Subsequently, the relevant risks and technical issues are further investigated. The identified and screened risks should then be clustered in one or more scenarios. The most critical scenarios should be identified for further quantitative evaluation. This means that HSE domain experts must be involved. Actually, it is essential they should be involved right from the start, when risk identification takes place.

2.4 The Risk Assessment Process

2.4.1 Risk-based site characterisation

This chapter describes the quantitative workflow on a generic basis. The very first issue is that the workflow is *risk-based*. Three generic risks present themselves: *leakage through the seal*, *leakage through the wells*, and *leakage through faults*. The workflow must first model the subsurface and the man-made structures (wells) in a kind of "standard mode" in which no leakages of any kind occur. Only when this preliminary phase has led to some understanding, and succeeded in obtaining such model(s), can the effects be studied of the uncertainties established in the qualitative risk assessment, and which led to the definition of the particular risks in some detail.

If no secure model can be constructed within the boundaries of what is known, the site under scrutiny will no longer be a candidate for storage.

2.4.2 Data completeness and uncertainty

The data input is never enough to fully constrain a model. Uncertainties are around in full measure, and hence just a few models is insufficient. Possible uncertainties that may lead to any of the generic risks must be faced. The keyword is *sensitivity analysis*. Sensitivity analysis touches upon a generic problem: how many runs have to be done? A provisional answer can be given with help of the theory of dimensional analysis (see Appendix 4), displaying the order of magnitude of the work (= the number of models to be run.). This amount of work will easily become prohibitive, if each uncertainty has to be taken into account. **Thus, proper discussions between operator and CA about the work to do are necessary. It can also be seen why the CA cannot stay aloof in the characterisation process, since fruitful discussions require an understanding of the prospective site from both sides.**
At this point, characterisation and assessment work can be streamlined such that it will not become prohibitive. These preliminary considerations lead to the quantitative aspects of the workflow.

2.4.3 Continuous risk assessment in a site characterisation

Site characterisation will be undertaken in *roughly* this order:

1. Data acquisition
2. Quick Analysis
3. Qualitative Risk Assessment
4. Geological Assessment (static model building, chapter 7.1)
5. Geomechanical Assessment (chapter 7.3)
6. Dynamic Behaviour (chapter 7.2)
7. Geochemical Assessment (chapter 7.3)
8. Migration path analysis (chapter (7.6)
9. Well integrity analysis (chapter 7.5)
10. Consequence Analysis (Human Safety Environment, HSE),

where step 4 leads to steps 5 through 9 and where steps 7, 8 and 9 can largely be performed in parallel. Steps 5 and 6 tend to be strongly linked. This 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. There are thus feedback loops in the process, which lead to a *continuous* risk assessment process.** The need for such a loop must be carefully monitored - see Chapter 4 on Communication Issues. These unanticipated risks may show up when the numerical work in the various steps is performed. It is to be noted here that performing numerical calculations is not just for the sake of “getting numbers”, but also witness how processes unfold in time. This is highly relevant if and when unexpected events appear pictorially and/or numerically.

The full risk assessment is the last step in which the results of the earlier steps are collected and summarized, possibly with probabilistic means. In Chapter 6 the qualitative risk assessment is described. Here the focus will be on the quantitative and theoretical aspects, of the remaining workflow. The reader is referred to Chapter 7 regarding the tasks, input, output, and interplay of the various technical disciplines.

2.4.4 Quantitative RA: tools, models, parameters and uncertainty

Having established what needs to be known in order to carry out the ultimate step of a quantitative RA, each of the different scenarios has to be considered and “carried” all the way through the steps identified in the bullets in section 2.4.3. The key point here is that computations 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 are agreed to be neglected? What effects should be included in any case? Which degree of accuracy is consistent with the available knowledge? For instance geologists tend to make very precise models on the basis of a limited amount of (well) data. They use their background knowledge to “fill the gaps”. Usually one can only be truly confident about trends. So, it might be wise to construct models of several (ten) thousands of cells that describe those trends, rather than constructing models of many millions of cells that mainly include estimated information. This might make life easier in performing the dynamic calculations (geomechanical, geochemical, flow) later on in the process.
- What is the uncertainty associated with each parameter? It may become clear that many essential parameters are not all 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 to reduce their uncertainty. Intimately connected is the question of how many runs should be performed to cover the parameter space adequately. A good start is to establish how many relevant independent non-dimensional parameters can be defined; one wants to obtain a complete set (see Appendix 4). From that information one can estimate the number of runs to be performed in order to reach adequate coverage of the parameter space. As mentioned in Appendix 4, this number is usually prohibitively large and a feasible number of runs is to be defined.
- Which tools (“software packages”, mathematical tools) must be used? It goes without saying that tools must be robust and precise. The actual models may be only large-scale in nature, nevertheless the calculations done on them should give trustworthy results. Actually, large-scale models, displaying trends, (“long wavelengths” in terms of Fourier components) are far easier to handle in flow calculations. So these models have the added bonus of reaching precise results with much less computational effort and time. This is highly relevant given the number of runs one may have to perform for adequate parameter space coverage.

Now the different steps (geomechanical modelling etc.) have to interface with each other. Basically the formula: “Output step n = Input step (n+1)” can be used. Close communication is needed between adjacent steps, and hence between their executors. If unexpected phenomena turn up within the work of one of the disciplines this may call for a discussion. It could then be decided that a feedback loop should be established between two or more disciplines. This issue is completely site-specific. It is vital to heed the point made in chapter 4.2 that a committee has to facilitate the discussions and monitor the workflow.

2.4.5 Description of tasks

In the end each model is “drawn” through the various steps. Finally one obtains CO_2 fluxes at the surface, if they occur at all; then HSE questions can be addressed. One must perform sufficiently many computations so that for all parameters that are indispensable for this task one can establish a (joint) Probability Density Function (PDF). All information regarding final uncertainty is contained in such a PDF.

From the perspective of the Storage Directive the following is important: Article 4.4 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 for the storage to be permanent. How the assessors should determine this is not specified in the directive. In fact, it is not specified what “permanent” should mean in practical terms. The same holds for an expression as “significant risk” [See the Definitions section (art.3) of the Directive, where various important concepts of the Directive are expressed in completely qualitative terms, EU, 2009]. The level of abstraction of the Storage Directive forces the national authorities to give a more concrete meaning to these terms when incorporated in the national law systems.

Finally there is an issue connected with the term “probability”. The concept of “probability” intrudes itself naturally into the assessment work, when dealing with many uncertainties. This document adheres to the *Bayesian interpretation* that is linked to the state of knowledge. It is important to have this in mind in order to avoid confusion, for instance when discussing results. Readers who want to obtain more information on the Bayesian interpretation of probability and the difference with the frequentist interpretation, are referred to Appendix 3, which defines the technical term “risk” as well.

2.5 Critical path of site characterisation study

The *critical path* of a RA project is governed by acquiring the necessary data, and then the entire modelling sequence, from geological assessment through dynamic assessment. If new concerns are found in any of these phases, some of the steps outlined in 2.4.3 may have to be repeated, extending the timeline of an RA project. The detailed descriptions in chapter 7 make this clear.

The experience of 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 activity.

The link between reservoir integrity and injection pressure often results in an iterative flow of results between geomechanical models and reservoir modelling.

3 Screening study

3.1 General description

Any site characterisation requires a preliminary screening in which sedimentary basins suitable for CO_2 storage are evaluated at a regional scale. In order to evaluate the storage potential of a selected area, which represents the first step and an essential pre-requisite for the CCS storage permit application, a screening study needs to be performed. First, criteria must be defined to be fulfilled by the prospective storage site. Then a screening plan will be drawn up to specify the screening actions. They will involve the following steps:

1. Collection and evaluation of available existing data.

Data	Objective
Borehole data (composite well logs, core measurements)	Evaluate for the presence of permeable storage formation and sealing cap rock
Seismic 2D and 3D (maps, surveys or digital seismic data)	Study the connection between the different geological elements at basin scale Map the areal extent and define the 2D and 3D geometric characteristics of the storage system, and possibly the properties of the rocks
Existing bibliography	Determine the overall structural setting of the area

2. Assessment of the seismicity of the area: potential storage sites should be in a geologically stable area, due to the risk of tectonic activity. This aspect should be carefully considered since the injection of CO_2 itself could activate quiescent pre-existing tectonic discontinuities and/or create new ones. These might represent preferential pathways for the CO_2 to migrate out of the reservoir, through the cap rock, into the overburden and potentially to the surface.

Data	Objective
Seismic hazard maps, seismic intensity maps, earthquakes catalogues	Assess the natural seismicity that could affect the storage complex

3. A preliminary estimation of the storage capacity must be performed. Obviously, in this step some assumptions will be necessary, and this leads to uncertainty as to the outcome. On account of the criteria this estimation may well act as a showstopper.

4. Investigation of possible conflicts of interest with other uses of the subsoil (*i.e.*, other activities with economic impact, such as for instance., water extraction, hydrocarbon production, etc.).

Data	Objective
Reports from/contacts with the local authorities	Identify activities that could interfere with the storage site
Maps and nautical charts	Map the occurrence of infrastructure already installed in the area

5. Estimation of the economic viability of the project. From the preliminary screening problems may arise whose solutions might not be economically viable (*i.e.* logistical problems). An example is the proximity to infrastructure to transport CO_2 from sources of CO_2 which can make the project too expensive.

A decision gate should be located at the end of the screening study considering the following potential showstoppers:

1. Lack of data and the inability to retrieve new data within acceptable costs and timeframe;
2. Obvious lack of sufficient potential storage capacity;
3. Obvious lack of containment potential;
4. Conflict of interest with other economic activities;
5. Seismic and other hazards;
6. Impossibility to monitor adequately.

If the overall conclusion is that the site is promising the data yet to be collected should also be discussed. *Operator and CA should have intensive (informal) contact over this, so as to enhance the quality and swiftness of the process*.

The CA should pay attention to relevant issues concerning available data; some of these are listed in the next two sections, for depleted hydrocarbon fields and saline formations, respectively.

3.2 Data issues for depleted Hydrocarbon reservoirs

1. Any additional date needed for a characterisation study that have not been acquired for hydrocarbon exploration and production (*e.g.* long-term field behaviour / far-field reservoir properties / cap rock integrity).
2. Data vintage and quality. In the case of vintage data re-acquisition might be needed. Seismic data can sometimes be re-processed to improve the quality of the resulting image of the subsurface.
3. The condition of the reservoir may have changed since the end of production, *e.g.*, because of water influx. Up-to-date measurements of reservoir pressure are required.
4. The condition of exploration and production wells always requires special attention and a recent well integrity analysis is required, to rule out any changes in the state of the wells since the previous analysis.
5. Any particular issues (such as liability, archiving, well description and abandonment conditions) should be investigated.

3.3 Data issues for saline Formations

1. If hydrocarbon fields are located within the same saline formation, data from these hydrocarbon fields may be relevant for the potential storage site. Data from these hydrocarbon fields should be collected.
2. The contribution from different storage mechanisms (residual trapping, mineralisation, dissolution, buoyant trapping) to the integrity and security of storage should be investigated and estimated.
3. Seismic survey data, particularly recent high-quality data, can often be used to resolve detailed geological structure in the subsurface. The full potential of seismic data should be

utilised to characterise the subsurface. Issues to consider include migration pathways, overburden structure, property mapping (of both reservoir and seal rocks).

4. Geological background knowledge should be used to predict expected variability in seal and reservoir characteristics; seismic data, if available, can provide input.
5. If well log data and cores are available, they could be used to predict or measure petrophysical parameters.

3.4 Conclusion

The screening study will determine whether there are potentially suitable sites for CO_2 storage within the area of interest. Where there is more than one potentially suitable site, a shortlist will be the outcome from the screening study. This shortlist contains sites for further examination of their potential as a storage location. It is expected that actual experience in many such screening and characterisation projects will enable the formulation of practically useful criteria in this respect. Each of the sites on the shortlist needs to be evaluated further, in a site-specific characterisation study. Which further data should be sought should be discussed between operator and CA under the provisos discussed in sections 3.2 and 3.3. The need for additional data should be made explicit.

In addition, at this stage it is decided whether the conditions to start the site characterisation process are truly present or not. This would include a first-order, high-level economic analysis. The goal should be to determine whether economic considerations might act as an immediate showstopper or not.

4 COMMUNICATION ISSUES

The majority of this report is concerned with rather technical matters. However, it is important for the organization of the work that there is full awareness of *communicative issues* that play a role at all levels. This was the experience in all the SiteChar site characterisation activities.

4.1 Interplay operator / competent authorities

In a document like the EU Storage Directive the CA feature at formal moments in the process that may lead to CO_2 storage. The guidelines on “Implementation of Directive 2009/31/EC”(EU, 2011) are a much welcomed addition in that they advise the CA on how to perform their tasks at such moments, or rather, what issues should have their full attention. From a practical point of view 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 suggest a massive program of research to be conducted, However, in any concrete situation certain parts of the proposed program might be more relevant than others. It has to be decided in an interplay between operator and CA which research is deemed sufficient in order to comply with the requirement of the Storage Directive that a geological formation and its surroundings shall be characterized and assessed as to its suitability 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 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 specific characteristics of the proposed site; it will also lead to a common understanding and definition of the performance conditions of a storage site and the focus of the activities to be carried out for a permit application**. It will also lead to a clearer focus for the operator on what to deliver at the formal moments in the process. Nevertheless, the different roles of operator and CA must remain clear.

To emphasise these points, one should mention a peculiarity of the work. Characterizing and assessing a prospective site is rather different from characterizing 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 an 3D earth model undisputed to the finest detail. There is still the well-known dichotomy of high resolution/strictly localized data (well logging data) and low resolution/global data (seismic data). Much, then, has to be filled in from the geologists 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 that the characterisation process be seen as a *mutual* concern of 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. This trust-building can only work if the two parties see the work as a mutual concern. The CA must have experts at their disposal who can take up such a communicative role - in fact, judging the work performed by the operator will anyway require non-legal and non-administrative activity on behalf of the CA.

Summing up*, the Operator and the CA must see the characterisation and assessment work as a mutual concern, and as a result must have both formal and informal contacts over the entire work period.*

4.2 Interplay of disciplines

In Chapter 1 it was mentioned that interdependencies and feedback loops in the workflow could play a significant role. This in turn entails that communication between the different disciplines (experts) must be attributed great significance. The interaction starts at the qualitative risk assessment, which is necessarily a multi-disciplinary affair. When the quantitative work starts there is the threat of different scientific disciplines becoming too isolated. Surely, there are necessarily contacts between the disciplines on questions of desired input and output, but after that has been cleared, there is a phase that every discipline acts on its own. Here lurks the danger of experts working in “splendid isolation”. This danger has to be mitigated.

Just as an example, the interplay between the geologists who develop the static 3D earth model and the dynamic modellers is crucial. The dynamic modellers have to work with the static modellers and must determine, among others, how they perform upscaling in a geologically sensible manner. But also, the geologist may have to adapt the static model when certain details appear to be crucial given the general flow characteristics found by the dynamic modellers.

The best way to have the connections between the specialists guaranteed is to have a small committee installed. This committee must organize regular meetings with all the workers. These meetings will keep everybody informed on the development of the site characterisation and will provide the information whether the study is properly focused.

These regular meetings further act as a kind of cement and enable the different disciplines to get in touch when they have to. This streamlines the workflow. Action plans must be formulated, as the discussions must lead to concrete activities for the specialists involved. At the meetings the risk register (see Chapter 6) plays a central role. Are the known risks being brought back 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 as soon as they are obtained and of the implications to their own work.

5 SITE CHARACTERISATION (1): Regulatory context

This chapter presents an overview of the regulatory context within which the characterisation and assessment process takes place. The main pieces of legislation state the goals to be achieved by this work, and describe the means to achieving this goal. This certainly holds for the EC Storage Directive.

5.1 EC Legislation

The EC Storage Directive (2009/31/EC), published on 23 April 2009, sets out the principles by which a monitoring plan for CO_2 storage projects should be designed. The Directive recognizes that monitoring is essential to assess whether

- Injected CO_2 is behaving as expected,
- Any migration or leakage occurs, and
- Any identified leakage is damaging the environment or human health.

Member States are therefore required to ensure that during the operational phase, the operator monitors the storage complex and the injection facilities on the basis of an approved monitoring plan designed pursuant to specific monitoring requirements. The operator should report the results of the monitoring to the competent authority at least once a year.

Once a project is completed and a site closed to the satisfaction of the CA, the liabilities associated with the site are transferred to the CA. At this point, monitoring should be reduced to a level which still allows identification of leakage. The Directive indicates that monitoring costs could be recovered from an operator (before site closure and revocation of a storage license) and that these costs should cover a period of 30 years.

Article 13 specifically addresses monitoring:

> *1. Member States shall ensure that the operator carries out monitoring of the injection facilities, the storage complex (including where possible the CO_2 plume), and where appropriate the surrounding environment for the purpose of:*
> *(a) comparison between the actual and modelled behaviour of CO_2 and formation water, in the storage site;*
> *(b) detecting significant irregularities*
> *(c) detecting migration of CO_2;*
> *(d) detecting leakage of CO_2;*
> *(e) detecting significant adverse effects for the surrounding environment, including in particular on drinking water, for human populations, or for users of the surrounding biosphere;*
> *(f) assessing the effectiveness of any corrective measures taken pursuant to Article 16 [Measures in case of leakage];*
> *(g) updating the assessment of the safety and integrity of the storage complex in the short and long term, including the assessment of whether the stored CO_2 will be completely and permanently contained.*
> *2. The monitoring shall be based on a monitoring plan designed by the operator pursuant to the requirements laid out in Annex II.*

In the EC Storage Directive it is also mentioned that a “corrective measures” plan has to be produced by the operator obtain a storage permit. This plan needs approval of the CA and has to be implemented as a minimum if and when cases of leakage or significant irregularities present themselves (Art.16). No specific demands are presented in the EC Regulation as to its contents.

Also a provisional post-closure plan is to be produced by the operator as part of a storage permit application. This plan has to be approved by the CA. No specific demands are presented in the EC Directive as to its contents.

5.2 Monitoring under the ETS

Amendments to the Monitoring and Reporting Guidelines for the EU Emissions Trading Scheme must also be adhered to by operators of CO_2 storage sites but are not discussed in detail here. The following is taken from the North Sea Basin Task Force report on monitoring and reporting in offshore environments (NSBTF, 2009).

Monitoring and Reporting Guidelines (MRG) for greenhouse gas emissions from the capture, transport and geological storage of carbon dioxide are laid down in the amendment of Decision 2007/589/EC.

The document, in particular the Annexes I (*e.g.* Section 4.3) and XVIII, specifies how emissions of the CO_2 storage activity have to be reported. The MRG places emphasis on the Verification, Accounting and Reporting of any leakage/emission.

The MRG (Section 4.3 of Annex I) states that a monitoring plan should be established. This includes detailed, complete and transparent documentation of the monitoring methodology of a specific installation, including documentation of the data acquisition and data handling activities, and the system to control the trueness thereof. Inter alia it should include the following specific items:

- Quantification approaches for emissions or CO_2 release to the seawater from potential leakages as well as the applied and possibly adapted approaches for actual emissions or CO_2 release to the seawater;
- Description of the installation;
- List of emission sources;
- Description of the calculation- or measurement-based method for quantifying emissions;
- If applicable, a description of continuous emission measurement systems;
- Compliance with the uncertainty threshold for activity data.

If there is no evidence for release of CO_2 to the seawater or atmosphere, or for emission on the basis of the Storage Directive, it is assumed that there are no emissions. If, on the other hand, there is an indication that CO_2 is emitted or released to the seawater or atmosphere (additional) monitoring techniques must be installed enabling the quantification of the leakage term(s). It is additional to the objectives in the Storage Directive. The monitoring activities can stop when corrective measures according to the Storage Directive have been taken and emissions or release can no longer be detected.

Potential CO_2 emission sources from the storage site which should be quantified are:

- Fuel use at booster stations and other combustion activities such as on-site power plants;
- Venting at injection or at enhanced hydrocarbon recovery operations;
- Fugitive emissions at injection;
- Breakthrough CO_2 from enhanced hydrocarbon recovery operations;
- Leakage from the storage complex.

6 SITE CHARACTERISATION (2): Risk Assessment as a continuous process; qualitative aspects.

6.1 Description of task

The activity of site characterisation has to be intimately linked with risk assessment (RA). This follows from the EU Storage Directive, article 4 numbered points 3 and 4 - this directive is to have been incorporated into the various national legal systems within the EU by 25th June 2011, and so is assumed to be valid.

In the RA the risks have to be determined in connection with questions on injectivity, storage capacity and containment. It is not sufficient to content oneself with generalities; site-specific assessment is called for. RA will eventually involve quantitative work, but at the outset an inventory has to be made of the risks potentially relevant for this *concrete* site. This “stock taking” activity is called *qualitative* RA. The *quantitative* RA is the whole of activities in which computation is used to follow up the leads from the qualitative RA. In chapter 2.4 this has been addressed.

6.2 Quick analysis, the preparation to RA

In preparation for the *qualitative* RA a quick analysis of the available data is performed. Specialists in the different fields of expertise, involved in the site characterisation, analyse the data from their viewpoint, by looking at features that might compromise storage integrity. These include inter alia the status of the wells in the reservoir, the condition of the reservoir seal and the extent to which faults are present in the reservoir or cap rock formations, the connection with other geological elements such as aquifers at basin scale. The presence of evidence of existing fluid flow, such as pock marks, chimneys and shallow gas is also relevant. The quick analysis is done on all available data, potentially more data than were used in the screening phase. So, more data – and especially more *storage-relevant* data – form the basis of the quick analysis. The aim of this step is to identify any problems related to the site before the study is continued. In practice, the experts consider all the available data, so as to find anything that could impede secure storage, or that could affect the site’s ability to meet the storage requirements (as described in section 2.1, under ‘screening study’). Two outcomes are possible:

- the prospective storage site is rejected;
- the site is still promising, notwithstanding issues in need of attention.

To reach a decision, criteria like the ones used in the screening phase are applied. In the first case, the characterisation process is terminated. In the second case, the results of the quick analysis represent the input to the qualitative risk assessment. The quick analysis does not, by itself, lead to hard decisions regarding the site characterisation study; it *does* lead to the formulation of issues to be taken into account and these are taken up in the qualitative risk assessment. Contacts between operator and CA are desirable in this phase, as this will lead to a fuller understanding of the situation by the CA and to a fuller understanding of the expectations from the operator in the subsequent steps.

6.3 Qualitative RA, part of a continuous process

The typical starting point of qualitative RA is a collection of all data regarding a specific candidate-site as available from previous activities. Often such a site was once a producing hydrocarbon field, in which case a large body of data may be available from the hydrocarbon field operator. In the specific case of a virgin saline aquifer the data might be scarce, leaving many more uncertainties to be resolved or taken into account in the risk assessment.

The process has to produce a (binding) guideline for further activities. The qualitative RA process typically answers the following questions:

- Which data have still to be obtained, for instance by exploration drilling?
- Which concrete risks are relevant and need to be addressed quantitatively in the site characterisation process?
- Which uncertainties are truly essential, so as to influence the (burden of) quantitative treatment by way of modelling?
- Should the current site be abandoned as a potential storage site?

Experts of various backgrounds have to co-operate to make the inventory. The team of experts should include geologists, reservoir engineers, geo-mechanics scholars, (geo)chemists, well technologists, (industrial) safety and HSE experts, biologists and certainly (geological) experts with site-specific knowledge. Additionally, representatives of the principal and the relevant governmental authorities should be invited as well as representatives of NGOs.

One should not lose sight of the fact that qualitative RA is not aimed solely at producing guidelines for follow-up work. It is also indispensable in winning public trust in any decision. Indeed, it is a way to show that the scrutiny is complete, and has been conducted in a responsible manner. For just this reason it is important to allow NGOs to participate and experience how things are done first hand. They could be invited to play an active role in the process. It is equally important to have the CA involved at this stage, since qualitative RA is an important guiding instrument for the next, quantitative (numerical) stages of the characterisation and assessment process (see Chapter 4 on communication issues).

The way in which the experts co-operate is largely a matter of convenience. It might be sensible to give those invited cogent information beforehand, and have them fill out a questionnaire prior to a round table meeting. This meeting is important as discussions, if facilitated properly, yield results that are better understood and accepted by the group of experts. These discussions will also potentially bring out differences of opinion. In addition, uncertainties are made more visible and this is obviously an important part of the process.

Experts are asked to propose events and processes that may yield undesirable effects, as well as to define *scenarios* of how certain mishaps may arise. These scenarios may play an important role in the modelling phase, when their evolution is followed and put to a numerical test.

It is sensible to define a so-called *risk matrix*: a severity-versus-probability diagram. This diagram gives an immediate feel for those risks that definitely need to be investigated in the workflow. It also shows at once which risks could possibly be dispensed with. Figure 6.1 shows such a diagram, with the number of risks in each category. Such a diagram is also an outcome of the qualitative RA.

The goal of site characterisation can now be re-formulated as follows: **the goal of site characterisation is to migrate the risks in the risk register from their position initially defined in the qualitative RA towards the origin through an improved understanding of (the uncertainty in) their severity and probability.**

If that understanding does not materialize and certain risks stay above some preordained level the site must be deemed unsuitable for storage.

During the follow-up steps, when modelling is underway and quantitative results are obtained, the understanding of the complexity of the site increases. As a result new risks may be discovered, that were hitherto overlooked or deemed irrelevant. Such a discovery must lead to renewed qualitative RA activity should the new insights affect the site characterisation process and quantitative RA. During the entire site characterisation work, the risk register should be maintained and updated. Discussions among the group of experts performing the work should be aimed at identifying new risks and at re-evaluating previously defined risks. Whenever necessary, the site characterisation work should be adapted to reflect a change in insight in the perceived risks.

The RA is a *continuous* process in which qualitative assessment and quantitative assessment are intertwined.

Although qualitative risk assessment is not immediately about numbers, it is possible to give a further numerical backing on account of the knowledge of the various specialists. To guide the work this is a helpful option. This is described in Appendix 2.

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 6.1 Risk matrix: probability vs. severity. Here only the number of risks is reproduced; in a full risk register the risks are described in their content.

6.4 Expectations and output from the Qualitative RA

To sum up:

1) Qualitative RA will point to potential risks during and after the storage activities of the proposed site. The results should be site-specific. The output can be put in diagrammatic form as a risk register and risk matrix.

2) Qualitative RA may point to major uncertainties and suggest further data collection in specific domains. For this reason involvement of the CA at this stage is essential; indeed, qualitative RA is guiding the next, quantitative steps in the workflow.

3) A risk assessment applied to a potential site determines and guides the research investigations. An unambiguous understanding of the storage site and storage injection scenario is essential to ensure that the research addresses the risks and uncertainties in terms of the requirements for the storage permit application.

4) Qualitative RA may help in gaining public acceptance when NGOs are explicitly invited to take part. In fact, this is the only stage in the site characterisation and RA process that lends itself to participation by parties other than CA and operator.

5) Qualitative RA will form the basic understanding for negotiations between the CA and the operator, including discussions leading to agreement of site performance indicators. This is a practical necessity as the EU Storage Directive in its Annexes produces a complete portfolio of research activities that may well be more than is required for a given site. The qualitative RA will indicate the level of scrutiny required for the different aspects of the site.

7 SITE CHARACTERISATION (3): The technical disciplines

This chapter describes the various disciplines in a site characterisation work. These are:

1. Static model building (section 7.1)
2. Dynamic modelling (section 7.2)
3. Geomechanical analysis (section 7.3)
4. Geochemical analysis and modelling (section 7.4)
5. Well integrity analysis (section 7.5)
6. Migration path analysis (section 7.6)
7. Socio-geographic analysis (section 7.7)

Sections 7.1 through 7.7 describe the input necessary to conduct the research, the results, the links with other workflow elements and possible risk factors. For each discipline, key concerns are highlighted.

7.1 Static model building

7.1.1 Description of tasks

Assessing the impact of CO_2 injection on the storage formation and potentially on the overall storage system requires the determination of the structural and stratigraphic setting. This must be done by creating a 'static' structural 3D geological model or Earth model of the storage complex. Prior to the construction of this model, discussions between experts in geology, flow simulation and other fields of expertise must take place to agree on the purpose of the model, capacity estimation, flow simulation, risks to be studied, uncertainties to be reduced. This should lead to a general understanding of the degree of details required of the geological model for the subsequent steps. This model will be updated according to the results of the site characterisation and from discussions between experts.

The different steps in the construction of the model are described in the following paragraph. Building surfaces either in seismic two-way-travel time or depth is the first step to understand the extent and the geometric characterisation of the geological complex. These surfaces are then incorporated into a 3D structured model that shows the spatial extent of both reservoir and cap rock. Of course this calls for the determination of a velocity model that is derived from seismic data. The model is then populated with reservoir-related properties or attributes from well log and core data. This system is called a *static model*, which is the input for a dynamic simulation workflow. Such models are built using a range of different types of software.

Static modelling may require more than only one model. Depending on one's hard knowledge and the uncertainties it may be necessary to start the quantitative site characterisation with several realisations of the model according to the uncertainty. Concentrating on just one model from the very beginning might be hazardous if uncertainty is large. The number of models used should then reflect the number of geological solutions that adequately reflect the available data and related uncertainties. Different solutions may be further refined or rejected as further information becomes available. In fact, the EU Storage Directive mentions the possible use of more than one model (See Annex I, Step 2, introductory text).

7.1.2 Input

Several elements and parameters are needed to build a static model. Basic input data, *i.e.*, data not resulting from other technical disciplines in a site characterisation team, are listed in Table 7.1.

Examples of these data are SEGY (seismic data format), physical parameters measured at a well or from laboratory tests.

Table 7.1 Input data for the static model building.

Data	Source	Usage
Previous seismo-stratigraphic and structural interpretation	Interpreted seismic data	Construction of 3D geological model at basin scale and reservoir scale
Seismic survey data	3D or 2D seismic survey	Interpretation of faults and stratigraphic surfaces.
Core data	Measurements on core samples taken in wells	Define the petrophysical distribution within the geological formations
Well log data	Physical measurements recorded in well	Define the petrophysical distribution within the geological formations
Porosity	Measurements on core samples taken at wells or derived from logs	Define the porosity distribution within the geological formations
Permeability	Measurements on core samples taken at wells or derived from porosity and/or logs	Define the permeability distribution within the geological formations
Interpreted faults	Interpreted seismic data	Define the fault pattern at the local (site) and regional scale
Mineralogy	Laboratory analysis on cores	Define distribution of geochemical properties
Hydrocarbon field/ HCIIP	Oil field reservoir parameter	Initial estimate of storage capacity
Outcrop data		Measure rock properties of analogue strata if material is not available for the selected geological formations
Fluid information	Pore water properties measured in well or on samples	Geochemical properties of the fluids within the reservoir
Well tops (stratigraphic interpretation of well log data)	Well log interpretation	Seismic data interpretation
Occurrence of shallow gas or gas chimneys	Baseline obtained from high resolution acoustic data	Identify possible gas leakage pathways related to the geological model
Geological knowledge from existing published papers	Bibliography	Geological- structural setting of the investigated area
Evidence of natural fluid flow to surface (that may already be described)	Baseline obtained from high resolution acoustic data	Construction of 3D geological overburden model

7.1.3 Input from other workflow elements

The static model represents the first step and serves as input for the dynamic, geomechanical and geochemical modelling. It is initially constructed using available data and may subsequently be improved when more data become available, from other elements of the workflow. These updates will be essential to reduce uncertainties. Table 7.2 lists input data for the static model from other workflow elements.

Table 7.2 Input data to the static model from other workflow elements.

Input	Source	Usage
Results from lab experiments (porosity and permeability)	Geochemical study, petrophysical experiments	Update the petrophysical properties distribution
Results from history match	Dynamic modelling	Update static model

7.1.4 Results

The static model, constructed on the basis of the data mentioned in sections 7.1.2 and 7.1.3, should represent the storage complex conditions as realistically as possible. The results are summarized in Table 7.3. The static model may be needed at different scales: a detailed model of the area near the injection site so as to allow an accurate modelling of the reservoir behaviour when CO_2 is injected and a regional model covering a (much) larger area so as to be able to assess the integrity of the storage site.

Table 7.3 Results from static modelling, that are used in other workflow elements.

Result	Description	Usage
3D model grid	3D gridding of the storage complex volume	Used in dynamic, geomechanical modelling
Porosity distribution	3D distribution of the porosity within the reservoir	Used in dynamic modelling
Permeability distribution	3D distribution of the permeability within the reservoir	Used in dynamic modelling
3D Mineralogy	3D distribution of the mineralogy of the reservoir	Used in geochemical modelling
Potential leakage points – spill points from structural closures in the top reservoir surface	Identify possible leakage pathways	Used in migration path analysis

7.1.5 Links with other workflow elements

The attributed static model output is input for the dynamic flow, geomechanical and geochemical modelling. A suitable model of the storage complex is thus necessary to define the appropriate parameters that will be used for the next modelling activities. Meanwhile, the structural setting (faults, fractures) is crucial for identifying potential leakage pathways and to maintain store integrity. It will be investigated within the migration path analysis and will contribute to the evaluation of the risk assessment.

The static model building should be "dynamic", in the sense that as new information becomes available, the model has to be updated so as to produce a reliable geological model.

7.1.6 Uncertainties and risk factors

The static model provides information mainly related to the geological assessment of the storage complex, from which possible risk factors and technical conditions not favourable for storage can be derived.

The uncertainties in a static model all derive from the fact that local, precise information is available at the wells, whereas everywhere else only regional-scale information is available (seismic surveys). The “gaps” are filled with the geologist’s background knowledge. Uncertainty arises especially in the case of low-quality data.

The risk factors are:

- Low porosity that will lead to low CO_2 storage capacity;
- Low permeability that may generate injectivity issues;
- Cap rock integrity, where the seal rock condition is not well known.

At this stage, the impact of these risks and the work required for their mitigation has to be estimated, in order to determine whether there exist solutions that are economically feasible and acceptable from a regulators point of view.

7.1.7 Key concerns

Static model building is particularly important, since its output is the very basis of all further steps. In the following, a number of key points are addressed that are particularly important for static model building. Some of these points raise questions of a more general nature.

Vision of storage site. A clear vision of the storage site and CO_2 injection scenario is needed. This stresses the necessity that in order to be able to really do the RA well in all respects a good static model is needed. This can only be the case if a “clear vision” is well known and understood, *i.e.* if one can ask the right questions for this site. One might add that it could be necessary to work with more than one static model, especially when finer points are unclear (*e.g.* is there a fault through the reservoir on our seismic data, or not?).

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 and also the coverage and vintage of the seismic data. Obviously, data on the characteristics of lithological formations obtained from the wells is 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 on seismic, or is it a matter of interpretation? This clearly adds to the workload. An alternative is to 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 sideburdens are modelled on a coarser grid and extend a sufficient distance laterally. The CO_2 migration path should be modelled with different tools, the results compared and discussed.

Model resolution. The resolution of the model depends of course of 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 a relatively high vertical resolution. Grid refinement at and around wells / faults should be possible "at will". It would be a bonus if the static model could be updated easily in this respect. Vertical gridding could be coarse in the overburden and / or the underburden, depending on the geological variability.

Software used. Commercially produced standard industry software is highly recommended in the different fields of expertise (like static model building and dynamic modelling) The 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 is a crucial issue. This should be tried out at the very beginning of the RA activities to avoid the subsequent necessity of duplicating a model in another format if software is not interoperable.

Collaboration between different experts. This issue has been dealt with early in this report on a general level. A number of issues nevertheless emerges.

1. Different software as used by different research groups can require model manipulation for obtaining compatible formats. Distortions of the original can result.
2. Build the static model together with the dynamic modellers as soon as possible. Fluid simulations can be quite sensitive to vertical resolution; this point should be taken up in this cooperation.
3. Exchange information on different software proposed to be used as soon as possible. Important in this respect are the issues on input / output formats.
4. Trivial but important: the overall research should be planned carefully, and this requires the relevant site-specific questions to be asked. This emphasizes the need for a good basic understanding of what the site is all about, and this again shows the importance of a thorough qualitative risk assessment early on.

Data acquisition.

- Licensing and provision of existing or commercially acquired data can take a long time, up to several months, and should be started as soon as possible. Significant effort may have to be spent in order to review the data.
- Significant cost may be involved in acquiring data (such as seismic data, well logs).
- Data may have unequal area coverage.
- There are always conversion issues (formats), especially with legacy data. Converting data to formats used by modelling tools may require significant effort.
- The interaction between components of the research and exchange of data between them is crucial if all activities are to be conducted and completed in a timely way. Best practice should be that the research follows a scheduled workflow that needs to be continuously updated to take account of changes during progress of the work.
- In depleted oil / gas fields there are abundant data, but sifting through them as to their relevance requires quite some effort. In saline aquifers there is not so much data in general. Some assumptions have to be made (*e.g.* on spatial sampling resolution).

All together it is concluded that static model building is a most critical phase: data gathering and contacts with different specialists from other disciplines make it a time-consuming business. As mentioned in Chapter 2.5, static model building is on the critical path of a site characterisation study.

7.2 Dynamic modelling

7.2.1 Description of tasks

Reservoir simulations of CO_2 injection and migration using a suitable structural geological model are required to predict several important aspects, such as:

1. Determining injectivity, storage capacity and technical feasibility constrained by threshold values of the maximum allowable reservoir pressure, plume arrival at a spill point or other limitations.
2. Evaluating containment on the short term (period during operations and after closure until transfer of responsibility to a governmental authority).
3. Evaluating containment in the long term including the fate and migration of CO_2 in the storage site. In principle, the models used to evaluate short-term containment could also be used for long-term simulations involving interactions with the aqueous phase. In processes such as long-term dissolution, fate and migration in the aqueous phase and mineralization are considered to be important, and dedicated specialized models should be used.
4. Providing input data for the risk assessment such as seal and fault integrity and plume migration, changes of pore pressures as a function of time and location.
5. Displacement of formation fluids such as brine in an aquifer, of natural gas in depleted gas field or of crude in oil reservoirs.

Depending on the specific aspects of the storage compartment under consideration, and also commercial reasons, a choice can be made between models ranging from simple analytical tank models to fully compositional reservoir models such as those derived in Eclipse, MoReS, STOMP, TOUGH II, COORES™, etc., as done for hydrocarbon reservoirs. Whenever the thermal impact of the injection is considered to be significant, a complex thermal simulation capability is also required. Coupled modelling is required, when dominant processes (which control the physical behaviour of the injection stream in the reservoir) appear to be mutually dependent. Whenever assumptions are required, conservative values should be used reflecting the degree of uncertainty for these parameters. In case input parameters or boundary conditions are uncertain, multiple simulations may be required to provide a sensitivity analysis on the cumulative impacts of parameter ranges on indicators of site performance.

7.2.2 Input

Table 7.4 describes the required input for flow modelling.

7.2.3 Input from other workflow elements

The dynamic modelling also requires input from other elements within the overall feasibility workflow, as described in Table 7.5.

7.2.4 Results

The output from the dynamic modelling serves as input for several other elements of the overall technical feasibility study, as specified in Table 7.6.

7.2.5 Links with other workflow elements

Initial reservoir simulations are undertaken following completion of the static geological modelling (essential input data) and are in turn followed by the geomechanical/geochemical simulations. Reservoir simulations therefore fall on the critical path of the overall study.

Table 7.4 Input for dynamic modelling.

Input	Source	Usage
Composition of the CO_2 injection stream	CCS project operator	Input for the reservoir model
Planned injection rates	CCS project operator	Input for the reservoir model
Configuration and location of wells	Hydrocarbon field operator	Input for the reservoir model
Hydrocarbon production data, initial hydrocarbons in place	Hydrocarbon field operator	History matching
Correct description of the PVT behaviour of CO_2 or mixtures containing CO_2 in particular near critical point: • Density • Viscosity	National Institute of Standards and Technology data (www.nist.gov) or other published data sets	Input for the reservoir model
Accurate initial pressure, temperature and composition of reservoir	Hydrocarbon field operator	Input for the reservoir model
Compressibility and viscosity of matrix and in-situ fluids	Hydrocarbon field operator	Input for simulation

Table 7.5 Input for dynamic modelling from other elements.

Data	Source	Usage
Static geological model: 3D fluid, rock, pressure and temperature data	Geological workflow or operator	Input for simulation
Bottom hole temperature	Facility engineering	Simulation of thermal impact
Bottom hole pressure limits	Geomechanical modelling	Limits for injection
Sealing or non-sealing character of faults	Geomechanical modelling	Flow modelling; pressure dissipation in reservoir
Changes in reservoir as a function of time, due to reservoir – CO_2 interaction	Geochemical modelling	Risk analysis, renewed capacity estimation

Table 7.6 Output from the dynamic modelling.

Output data	Use
Pore pressure and temperature as function of time and location	Geomechanical evaluation
Fate and migration of CO_2	Geochemistry
Location of injection wells, injection rate for each well	Surface engineering
Storage capacity	Surface engineering
Near well temperatures	Surface engineering

Links with other elements of a site characterisation study include the following.

- Static modelling. In the case of hydrocarbon reservoirs, a history match of production data is required to test the model used for the dynamic modelling. A match between measured and predicted production data is obtained by adjusting (parts of) the dynamic model. The changes are fed back to the static model, where applicable.
- Well integrity. Plume migration must be cross-checked with the location of existing wells. The integrity (safety) of wells in contact with the CO_2 must be ensured.
- Geomechanical modelling. The geomechanical analysis results in the boundary conditions for the bottom hole pressure, and the pore pressure near the cap rock. The temperature field that follows from the dynamic modelling is an input for an analysis of thermal stress in the geomechanical modelling; this may lead to an update of the boundary conditions for the bottom hole pressure.
- Geochemical modelling. The pressure and temperature fields are input for the geochemical modelling of interaction between fluids (including CO_2). The choice of injection wells is one of the inputs for the storage site development plan. In case of re-use of existing installations and wells, the choice of injection wells determines which wells – if any – are to be abandoned, which are to be converted to injectors and which to monitoring wells. In the case of new installations and wells (for example, for a virgin saline formation that is developed for CO_2 storage), the injection strategy determines the location of injection site or sites.
- Socio-geographic analysis. Like the previous item, the choice of injector wells can be affected by current land use, the proximity to (densely) populated or used areas and vice versa for sparsely populated or used areas.

7.2.6 Uncertainties and risk factors

Modelling of the dynamic behaviour of the storage complex can produce results that impact the feasibility of storing CO_2. Such results are input for the quantitative risk assessment. These results can include one or more of the following aspects of risk and uncertainty.

- Injection rates may be lower than the supply rate. This could result in additional storage sites being required.
- Storage capacity could be different to that anticipated, *e.g.* from a high-level screening study. Again, this can lead to higher than expected storage costs.
- CO_2 migration simulations show CO_2 will travel to an area too shallow / near a geological fault / near a potential leakage pathway.
- Low porosity and permeability (tight) reservoir conditions, resulting in smaller than expected capacity and injection rates.
- Critical phase conditions of the storage system (pressure and temperature conditions pre-injection).
- Pressure build-up due to (unexpected) compartmentalisation of the reservoir or boundaries closed to fluid flow.
- Requirements for additional heating of the CO_2. Heating is expensive and will affect the storage costs.

- Predicted simulations do not match the observed results. This may occur once injection is started, in which case it will lead to updating of the static model and a re-iteration of the dynamic and geomechanical modelling.

7.2.7 Key concerns

The following points merit special attention in dynamic modelling.

- There is a need for close interaction with the static modellers, in order to streamline and iterate parameters for the dynamic simulation scenarios. Close interaction with geomechanical modellers is also needed, to agree on injection scenarios, and the use of compatible modelling software.
- It is advisable to consider dynamic and geomechanical modelling as coupled processes that must be modelled simultaneously.
- 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.
- It is important to define proper boundary conditions, especially when comparing regional and local model simulations.
- Data availability is always a major concern:
    - Start the collection of data early, as it is a time-consuming process.
    - There is added value in the participation of the hydrocarbon field owner (if appropriate) to have access to detailed reservoir properties. Especially, information on reservoir heterogeneity is much welcomed, as it is a highly influential input.
    - Fault behaviour is key information. Here sensitivity analysis is strongly advised as fault properties are not generally well-known.

7.3 Geomechanical analysis

7.3.1 Description of tasks

Geomechanical simulation of the storage area is essential to ensure the storage integrity under CO_2 injection and forecast the pressure propagation over time.

Since injected supercritical CO_2 is less dense than water, CO_2 is driven up due to buoyancy forces. This means that leakage can occur through vertical fluid migration via the top seal, faults/fractures and existing well penetrations and, in the case of an open aquifer, also through lateral migration. Therefore, it is essential to characterize the continuity and the thickness of the seal rock, the potential migration pathways (faults and wells), and the mechanical behaviour of the reservoir and seal (rock strength, fault/fracture stability and maximum sustainable pore fluid pressures). Migration through existing well bores and non-sealing faults are considered the greatest risks in CO_2 storage integrity considerations.

Increases of the formation pressure, due to injection rate and volume of CO_2 and buoyancy forces, might affect the subsurface. Understanding the pressure regime is thus essential to estimate the maximum sustainable fluid pressures for CO_2 injection that will not induce fracturing and faulting. This requires fluid flow modelling (with proper permeability and porosity evaluation), and also, to ensure a good mechanical analysis, the characterisation of initial stresses, fault distribution and rock strengths. In saline formations, pressure management will prove essential to control deformation in the surrounding rock matrix. Too high overpressure values resulting from injection might reactivate pre-existing faults or generate new fractures and compromise store integrity.

This task will not deal with leakage through wellbores, as this should be done via a "local" dedicated model.

7.3.2 Input

Data for geomechanical baselines (see Table 7.7) can be extracted from interpretation of logs and experiments on cores. If data are not available, published literature can be consulted to determine a range of values to be tested.

7.3.3 Input from other workflow elements

Data presented in Table 7.7 allows the establishment of the geomechanical baseline. However, this information has to be updated according to the fluid flow simulation and the geochemical analysis results, which includes changes in the porosity and mineral composition. The input data needed are summarized in Table 7.8.

Pressure and temperature differences (ΔP and ΔT) data, output from the dynamic modelling, are input for the geomechanical modelling. They represent variation in pore pressure and in temperature (relative to a reference date).

Table 7.7 Input data for the geomechanical analysis.

Data	**Source**	**Usage**
Initial geomechanical rock properties (E, ν)	Sonic log/ laboratory experiments	Loading of the geomechanical modelling
Initial stress	Leak-off test & density log / world stress map	Idem
Failure criteria for seal and fault (friction angle, cohesion)	Laboratory experiments / material laws	Idem
Thermal dilation coefficient	Laboratory experiments	Idem
CO_2 impact on rock mechanical properties (E, ν, friction angle, cohesion)	Laboratory experiments	Idem

Table 7.8 Input data for the geomechanical analysis from other workflow elements.

Input	**Source**	**Usage**
Regional static model with 3D fault framework	Geological static modelling	Geomechanical model geometry
$\Delta P(x,y,z,t)$, $\Delta T(x,y,z,t)$	Dynamic modelling	Loading of the geomechanical modelling
Initial porosity (x,y,z)	Geological static modelling	Geomechanical model parameters
Porosity (x,y,z,t)	Geochemical modelling	Geomechanical model parameters
Mineral composition (x,y,z,t)	Geochemical modelling	Geomechanical model parameters
Weakness area to be considered	Migration path analysis	Areas where failure criteria has to be evaluated

7.3.4 Results

Once the geomechanical modelling is performed, the outputs are strains and stresses through the entire model (Table 7.9). The modelling will also result in failure criteria (pressure limits) that are input for the dynamic modelling and risk analysis.

Table 7.9 Results from the geomechanical analysis.

Result	Description	Usage
Porosity (*x*,*y*,*z*,t)	Updated porosity	If significant variation: dynamic modelling / geochemical modelling
Pressure limit	Injection pressure limit	Dynamic modelling / risk analysis
Weakness areas	Confirmed weakness areas and recommendations for monitoring	Risk analysis

7.3.5 Links with other workflow elements

- Geological static modelling: a structural model up to the surface, including faults, attributed with initial porosity is required at the beginning of the geo-mechanical modelling (non-iterative). The consistency of geomechanical data (Table 7.7) with lithostratigraphical units has to be checked.
- Geochemical modelling: updated porosity and mineral composition are required to compute updated mechanical parameters. The porosity update could be iterative.
- Dynamic modelling: pressure and temperature variation computed by dynamic modelling are used to load the geomechanical modelling. Geomechanical modelling also gives the limits to injection pressure to help in determining injection strategies. This is an iterative process between dynamic and geomechanical modelling.
- Migration path analysis: results can be used to help in identifying possible weak areas where the failure criteria have to be determined.
- Risk analysis: geomechanical modelling gives information on the risk of geomechanical failure for a given injection scenario.

7.3.6 Uncertainties and risk factors

One concern is the limited availability of relevant data to obtain an estimate of geomechanical behaviour, which integrates geochemical aspects.

Another risk factor that may occur is when the pressure limit is reached before the expected volume of storage is achieved. It may concern the fault behaviour (reactivation) and the integrity of the cap rock. Too high pressures might also propagate existing fracture networks from the reservoir to the cap rock.

7.3.7 Key concerns

- Proper pressure and temperature boundary conditions need to be known.
- Availability of data is an issue, in particular:
    - Information on fault properties;
    - Overburden properties;
- Assumptions must be shared among the team of experts.
- There is a need for close operation with the dynamic modellers.

- o Geomechanical modelling establishes crucial seal rock fracture pressures, which is a constraint on the injection scenario(s).
- o Coupled dynamic and geomechanical modelling is needed.
- o Consistency of models must be ensured.
- o Software / format compatibility must be assured before commencing dynamic and geomechanical modelling.

7.4 Geochemical analysis and modelling

7.4.1 Description of tasks

Geochemical reactions such as dissolution and precipitation are key trapping mechanisms and are essential to understand long-term storage activities. Once dissolved in brines, CO_2 can induce geochemical processes such as the dissolution/precipitation of rock-forming minerals, which may affect the reservoir and/or cap rock integrity. Moreover, zones of weakness (faults, fractures, wells) represent preferential pathways of leakage to the subsurface or to drinkable water.

Several experimental and modelling exercises have to be conducted to evaluate the reactive mechanism induced by CO_2 injection:

- Geochemical reactions induced by CO_2-rich fluids, such as dissolution/precipitation processes in the reservoir and cap rock formations. The timing and process of mineralogical alteration has to be evaluated, according to the geological and hydrological features of the investigated area.
- Alteration of rock sealing integrity due to CO_2 injection, as a consequence of lower interfacial tension of the CO_2-water system compared to the hydrocarbon-water system initially present in the reservoir. The lithology strongly influences the wettability and interfacial tension of CO_2.
- Interaction between injected CO_2 and cement in wells.

Geochemical and solute transport modelling will allow the understanding of gas-water-rock interactions. Site-specific data (pressure, temperature, porosity, permeability and salinity) will be required to run hydro-geochemical simulations. The simplest model consists of considering geochemical reactions towards an equilibrium state. Speciation-solubility models are called zero dimension models since they do not consider any spatial or temporal information. They model the geochemical fluid/rock interactions occurring between the rock matrix and the CO_2 saturated brine, in particular, mineral dissolution and/or precipitation reactions, from initial mineralogical assemblage of the solid matrix and speciation of the initial fluid, containing the dissolved CO_2. In addition, the solute transport models account for the fluid flow and the kinetics of precipitation/dissolution of minerals. However, these models remain local, and accounting for spatial variations requires a coupling between the geochemical modelling and the fluid flow modelling.

In addition other processes might be considered, such as:

- Microbial reactivity that could influence carbonate precipitation. Through bio-mineralization processes subsurface microbiological processes may affect CO_2 injection, stability of primary minerals as well as the precipitation of secondary mineral phases. An adaption of geochemical models could enable this kind of microbial process to be considered and the rate of carbonates bio-precipitation to be quantified. Biochemical processes may accelerate the mineral carbonation, which is known to be the most stable and secure trapping mechanism for long term CO_2 storage.

- Composition of gas initially present in the reservoir in terms of major gases (CH_4, C_2 to C_5, N_2, H_2S, H_2), noble gases (He, Ne, Ar, Kr, Xe) and carbon isotopic composition ($\delta^{13}C$). The presence of such elements may indeed control the exchange between fluid phase and gas phase and thus determine the amount of dissolved CO_2 at the reservoir scale, with a 1D model diffusion, in the long term. This effect could occur a long time after the injection phase has finished and can be modelled with a 1D diffusion model, both at the sampling scale as well as at the reservoir scale.
- CO_2 gas diffusion processes. This effect could occur a long time after the injection phase has finished and can be modelled with a 1D diffusion model, both at the sampling scale as well as at the reservoir scale.

The outcomes of such models are, amongst others, the change of porosity and permeability due to chemical reactions induced by the presence of CO_2.

7.4.2 Input

Input data for each site includes the chemical composition, temperature and pressure of the initial aqueous solution and the mineralogical description of the reservoir and the cap rock. The thermodynamic data for minerals, gases and aqueous species are obtained from relevant databases. Thermodynamics refers to the equilibrium state of the system, and is the key to understand, for example, whether calcite would dissolve or precipitate in a specific solution.

However, many processes are rate-limited by kinetic parameters so that accounting for kinetics is essential to determine whether reactions will occur or not. This requires information about the rate of the formation water (brine) flow that will control the equilibrium state. Information about the direction and rate of brine flow is also required to select samples in areas that could be affected by the CO_2 brine.

Table 7.10 Input for the geochemical elements in the workflow.

Data	Source	Usage
pH / alkalinity	Field measurement on formation water (brine) samples	Initialization of chemical reaction
T, p		
Dissolved oxygen, organic matter (for hydrocarbon field), any dissolved species		
Dissolved CO_2 (or P_{CO2})		
Salinity		Required / possibly from literature
Na, K, Ca, Mg, Al, Fe, Mn, SiO_2, SO_4, Cl, S, PO_4	Laboratory measurements on brine samples	Initialization of chemical reaction
Mineral identification of rocks or well cements	Laboratory measurements on rock samples.	Initialization of chemical reaction
Mineral abundances	Cation Exchange Capacity measured either on total rocks or on clays	Idem
CEC		Idem
Mn and Fe extractable oxides		Required for an estimation of redox
Surface area, porosity	Laboratory analyses	Required to estimate brine/rock ratios and the available reactive surface areas

Geochemical modelling requires knowledge of both the chemical composition of the fluids and of the rock matrix. The input parameters for geochemical modelling are listed in Table 7.10. The rock matrix should also be characterized regarding the concentration of primary and secondary minerals in order to assess the solubility of the brine chemistry. X-ray diffraction, petrographic studies, scanning electron microscopy and electron microprobe can be used for this purpose. For fine-grained minerals, transmission electron microprobe is an adequate tool to provide such data. In addition, cation exchange capacity (CEC) may be useful to measure when ionic exchange between brine and clay minerals is expected to control brine chemistry. Finally, estimation of the amount of amorphous iron and Fe or Mn oxides might be needed because of their high adsorption capacity and their potential to provide a rough estimate of the redox conditions of the system.

Redox is an important parameter since secondary minerals may precipitate, depending of the redox of the aqueous phase (system). Even if a small amount of these secondary phases are present, they may strongly influence changes in the porosity, permeability and, hence, injectivity parameters.

Specific input data (Table 7.11) is required for depleted reservoirs, in order to characterise the initial system, before injection occurred. In that case, it is possible to follow the concentrations to deduce any change in the system due to injection. It also makes it possible to check whether the modelling is in good accordance with the fields observations.

Table 7.11 Elements and type of analyses to geochemically characterise the initial system (depleted reservoir) and the impact of the other end-members (oxycombustion process and injected CO_2 which comes from this capture process). The left column represents the three main end-members which must be analysed to characterise the system.

Samples from	**Analyses**	**Elements**	**Usage**
Depleted reservoir	Major gases concentration	CO_2, C_1 to C_5, H_2S, N_2, H_2O	Initialization of chemical reaction Reference for monitoring (δ^{13} C)
	Noble gases concentration	He, Ne, Ar, Kr, Xe	
	$\delta^{13}C$	CO_2, C_1 to C_5	
	Noble gases isotopes	^3He, ^4He, ^{36}Ar, ^{40}Ar	
Injected CO_2	Major gases concentration	CO_2, O_2, N_2, H_2O	Idem
	Noble gases concentration	He, Ne, Ar, Kr, Xe	
	Isotopic ^{13}C: $\delta\ ^{13}C$	CO_2	
	Noble gases isotopes	^3He, ^4He, ^{36}Ar, ^{40}Ar	
Capture process (in case of oxycombustion)	Major gases concentration	$O_{2,}$ impurities	Initialization of chemical reaction
	Argon concentration	Ar	
	Noble gases isotopes	^{36}Ar, ^{40}Ar	

7.4.3 Input from other workflow elements

Input data as described in section 7.4.2 give only local information. Accounting for spatial variations requires a coupling with dynamic flow modelling. Such information comes from the static model that has been attributed with flow properties and also geochemical properties, see Table 7.12.

Table 7.12 Input data for geochemical analysis from other workflow elements.

Input	Source	Usage
Incoming flow (composition and kinetics)	Dynamic modelling	Geochemical reactions and kinetics
p(t), T(t)	Dynamic modelling	Initialisation of chemical reaction
Porosity / Permeability	Static modelling / Dynamic modelling	Impact of porosity and permeability on chemical reactions

7.4.4 Results

Equilibrium geochemical models update the fluid compositions according to reservoir conditions, where samples can not be preserved at in situ conditions. Mass transfer geochemical models simulate the reactions between CO_2, formation fluids and formation mineralogy.

The outcome of geochemical analysis (Table 7.13) is an update of mineral and fluid composition that affects the permeability and the porosity distributions.

Table 7.13 Results from geochemical analysis.

Result	Description	Usage
Mineral composition	Update	Geomechanical modelling
Fluid composition	Update	Dynamic modelling
Porosity	Update	Dynamic modelling and geomechanical modelling
Permeability	Update	Dynamic modelling

7.4.5 Links with other workflow elements

The pressure, at the end of injection, the displacement of gas phase versus liquid phase, and the rate of CO_2 dissolution are determined using a transport model. A speciation-solubility model allows a coupled reactive mass transport model that both includes temporal and spatial information about chemical reactions, pressure, temperature (in most cases fixed), evolution of pH and permeability and porosity.

- Geomechanical modelling: updated porosity and mineral composition to compute updated mechanical parameters;
- Dynamic modelling: geochemical analysis results provide updated porosity and permeability data. This process could be interactive;
- The uncertainties on fluid composition (porosity and permeability) and also on rock mineralogy play an important role for risk assessment.

7.4.6 Uncertainties and risk factors

The main risk relies on the accessibility of data and samples. In addition, in case of very low permeability, it may be difficult (and expensive) to determine this value and to perform relevant geochemical analysis. Another risk may come from the presence of secondary mineral phases which are in a low amount – likely uncertain and difficult to estimate - but which can play an important role on the CO_2 injectivity and reactivity. The geochemical composition variability of the injected CO_2 (that may come from many sources) is a possible risk factor for prediction of mixing processes between the end-members and possible leakage. A possible risk associated with geochemical causes is a reduced permeability and injectivity near a well bore.

7.4.7 Key concerns

- A good understanding of the mineralogy of the host rock is essential for a reliable geochemical study. Core analysis from the immediate vicinity is important.
- Information on well cement and other well material is often not available. This is problematic.
- There is a need for the evaluation of geochemical modelling software that accommodates reactions in oil and gas and water-bearing strata (if relevant).

7.5 Well integrity analysis

7.5.1 Description of tasks

Potential migration from the reservoir along existing and abandoned wells is generally considered as the most important risk associated with CO_2 storage. The well system forms a potential conduit for CO_2 migration because wellbore cement may be susceptible to chemical degradation under influence of aqueous CO_2 or to mechanical damage due to operational activities. Wet or dissolved CO_2 forms a corrosive fluid that could induce chemical degradation of the oil well cement or polymers potentially enhancing porosity and permeability. It could also stimulate corrosion of steel, which may lead to pathways through the casing. Furthermore, operational activities (*e.g.* drilling, pressure and temperature cycles) or natural stresses can result in mechanical degradation through the development of tensile cracks or shear strain, enabling highly permeable pathways to develop. Finally, poor cement placement or cement shrinkage could cause the loss of bonding between different materials and lead to annular pathways along the interfaces between cement and casing or host rock.

According to the EC Storage Directive all existing wells which might be in contact with the injected CO_2 and future wells required for CO_2 storage activity have to be considered in the assessment. With respect to the evaluation of long-term integrity of the geological storage system, special focus has to be paid to the quality of wells penetrating the storage reservoir. Previously abandoned and therefore inaccessible wells have to be regarded as key risks, especially when they were drilled before modern abandonment regulations and practices were in place.

To ensure secure long-term containment of the CO_2 underground, some criteria for well barriers (Figure 7.1) have to be established and performance tests in the presence of CO_2 have to be conducted.

The well barriers isolate the well fluids inside the wellbore and prevent uncontrolled discharge to the overburden above the cap rock or to the atmosphere. These typically include the cement section outside the production casing adjacent to the formation rocks and the production casing itself. Special attention has to be paid to the existence and performance of the cement (abandonment plugs and cement sheath) at the cap rock level(s) in order to restore the natural integrity interval.

Generally, the assessment should include direct measurements of the quality of the barriers after placement (such as cement evaluation logs and pressure tests) and during the productive life of the well (*e.g.* annular pressure information). A proper well integrity analysis is therefore highly dependent on the history of the well and on the availability of any recorded data related to the design of the well, the state of the wellbore materials used and their performance in the presence of CO_2.

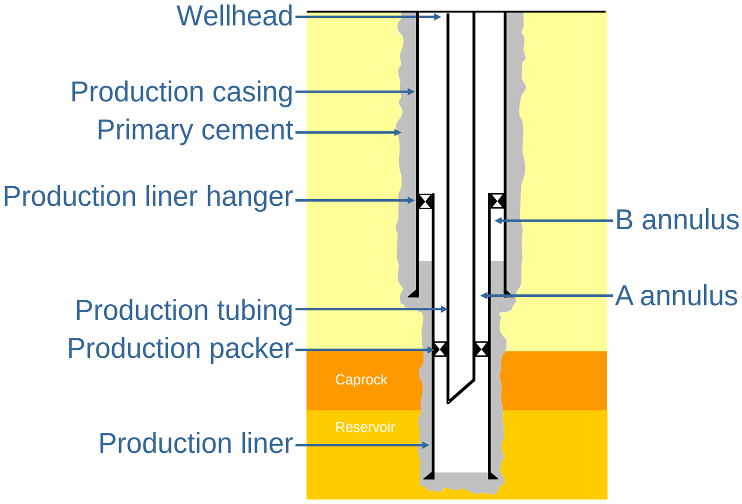

Figure 7.1 Well barriers in a generic well configuration.

When direct measures for the determination of the well barrier integrity are unavailable, indirect measurements have to be used. Such evidence includes drilling information on logs or cement losses.

Wells drilled during CO_2 storage operations (as well as existing accessible wells) can be designed, completed and abandoned according to requirements applicable to long-term containment, as required by the EU Storage Directive. In order to be fit-for-CO_2 storage, some barriers of existing wells may need to be upgraded, based on the assessment of, for example, wetted areas of pipes. It should be stated in the integrity assessment which barriers need to be 'upgraded' for CO_2 service by considering respective robustness criteria. If there is no data to guide the analysis of the condition of the barrier, the data gaps should be stated clearly and ways to reduce uncertainties investigated. A proper evaluation of the performance of the well barriers is essential for the subsequent steps risk assessment of the wells and the selection of potential corrective measures.

7.5.2 Input

In order to perform a proper well integrity assessment a comprehensive set of information on the wellbores is required. Information on the history of the well is crucial. Data on number, age, location and configuration of the wells are vital to gain detailed information on the existence and state of the well (barriers) and to define potential HSE risks generated by the wells.

Usually the desired data and conducted works, like pressure tests, are recorded in different kind of reports (*e.g.* final well, completion or work over reports), in well logs or geological maps. Table 7.14 lists the information, which is essential for the evaluation of the integrity of the wells in the storage area.

7.5.3 Input from other workflow elements

Essential input is required from the dynamic modelling task as well as from the geochemical and geomechanical simulations (Table 7.15). Information on potential plume migration, composition and the pressure evolution in the reservoir are vital to estimate the risk of potential migration in and along the existing wells.

The static model provides information on the exact location where the wells penetrate the cap rock and enter the reservoir.

Table 7.14 Input data for well integrity risk analysis.

Data	Source	Usage
Well tops	Interpreted well logs, Composite Well Logs (CWL)	Locate cap rock intervals
Location and number of wells	Well reports, maps	Migration path analysis, re-entry, static model, etc.
Age (of drilling and abandonment)	Well reports	(Abandonment) configuration, used materials
Depth	Well reports, data base	Reservoir penetration
Well design	Well reports	Number and type of casing(s)/tubing/liner
Deviation	Well reports, data base	Quality of cement jobs, location of reservoir penetration
State of cement plugs	Well reports	Identification of potential leakage pathways
Integrity tests	Well reports	Failures during production life, integrity of completion
State of primary cement sheath of production liner and casing	Cement Bond evaluation Logs (*e.g.* CBL)	Identification of potential leakage pathways
State of the casing(s)/liner	Wireline logs (*e.g.* caliper)	Identification of potential leakage pathways
Type of production packer and production liner hanger	Well reports	Identification of potential leakage pathways
Annular pressure	Database (recorded pressures)	Information on leakage
Well history	Well reports	Information on temperature and mechanical stress during production

7.5.4 Results

The outcomes of this task describes the potential weak points of each of the existing wells in the storage area and will point out leakage risks associated with the wells in place (Table 7.16). The potential risk, together with the accessibility of the wells, is therefore crucial for any risk analysis issues, for economic considerations and for establishing a proper remediation plan. Furthermore, the results of this workflow will be adopted in the migration path analysis.

7.5.5 Links with other workflow elements

This task is included explicitly in the integrity evaluation (migration path analysis), and it links back to every data acquisition and simulation element in this study. Notably, it should be established which wells are intersected by the CO_2 plume.

7.5.6 Uncertainties and risk factors

Well integrity issues present major hazards in the context of underground storage of CO_2. When the status of a well in the storage area does not match the safety standards for underground CO_2 storage or crucial information on the status of the well barriers is missing, there is a high impact on both HSE issues as well as for the economic feasibility of the storage project. Detected weak spots in the wells require adequate treatment, addressed in a remediation plan by the means of defined corrective measure. Especially in the case of abandoned wells these counter measures can be (technically and economically) taxing and may become a showstopper. For accessible wells the conduction of remediation work is generally technically feasible, but can be expensive.

Table 7.15 Input data for well integrity analysis from other workflow elements.

Input	Source	Usage
Lithostratigraphy	Static model	Define seal interval and intersection of well and cap rock base
Intersection of well and bottom of the cap rock	Static model	Locate precisely potential migration pathways
Pressure limits	Geomechanical analysis	Limits to bottom-hole pressure
Pressure at intersection cap rock –wells, as a function of time	Geomechanical analysis, Dynamic modelling	Mechanical stress load for well system
Temperature at intersection cap rock –wells, as a function of time	Dynamic modelling	Mechanical stress load for well system
CO_2 plume propagation	Dynamic modelling	Specify wells exposed to CO_2
CO_2 plume composition	Geochemical simulations	Intensity of corrosion of well materials
pH	Geochemical simulations	Material degradation/ corrosion potential
Formation fluid composition/ saturation	Geochemical simulations	Material degradation/ corrosion potential

Table 7.16 Result from well integrity analysis.

Result	Description	Usage
Well barrier defects and well integrity issues	Various issues possible	Define leakage pathways; input for migration path analysis
		Risk evaluation
		Design of corrective measures
		Create remediation plan
		Economic aspects

7.5.7 Key concerns

The following are of particular concern:

- Availability of proper data
    - Lack of proper data (*e.g.*, status of the cement, well casing).
    - In situ observations of wells are required. Such operations are very expensive. Estimate cost and the timing of such operations as early in the process as possible.
- There may be a need to study a worst-case scenario and estimate the associated risks, to side-step the problem of the lack of data.

7.6 Migration path analysis

7.6.1 Description of tasks

The aim of migration path analysis is to quantify the areal extent of CO_2 stored in the underground over longer time periods. It also serves to evaluate and estimate potential CO_2 migration and leakage pathways and the potential gross leakage of leakage events (flux rates). The main factors controlling the migration and potential leakage pathways are:

- Topography of the storage reservoir;
- Reactivation and leakage along existing faults;
- Hydraulic fracturing and leakage due pressure build-up;
- Leakage through abandoned well(s);
- Intra reservoir baffles and variations in permeability;
- Reservoir hydrogeology.

These factors are generally not well known. It is important to quantify the uncertainties in the input parameters and to model how these uncertainties may influence migration paths and leakage rates.

There are at least two main ways to perform migration path analysis. One is to use a basin modelling tool to simulate how injected CO_2 will migrate over time, both on short and long time scale. Migration paths in the reservoir will then be simulated, including capillary leakage through the cap rock and fault leakage. Uncertainty can be addressed by varying the input parameter and using a Monte-Carlo sensitivity approach (if computation times are not prohibitively long). Well integrity data should be input from the results of well integrity studies.

Another approach is to use simulation results from static and dynamic modelling as input to the migration path analysis. This approach utilises plume migration modelling from dynamic modelling software and spill point analysis for the top reservoir surface obtained from static modelling. Potential leakage points from wells should also be addressed. Fault properties could be input from the results of geomechanical modelling.

The challenge is to integrate simulated results and knowledge from the different disciplines, to make a realistic sensitivity analysis on the risk of leakage. The complexity of the modelling depends on the geological storage complex. Software that takes all the different leakage risks properly into account and that can do multiple simulations to estimate the uncertainty effectively would represent a significant improvement.

7.6.2 Input

Migration path analysis requires detailed knowledge about the geological setting; *i.e.* interpreted seismic horizons from reservoir and cap rock, pressure and temperature, interpreted faults (throw, age and possible active periods should also be included), well logs with lithological units interpreted; see Table 7.17. This data would be available from a static model. If they do not exist, they should be created for the migration path analysis, using realistic default values.

In addition, information is required about the tectonic regime, structural setting, wells, existing hydrocarbon fields, licence block boundaries and surface infrastructure.

Table 7.17 Input for the migration path analysis.

Data	**Source**	**Usage**
Maps of top and base surfaces of reservoir unit (s)	Interpreted seismic horizons	Build 3D basin-scale model
Interpreted units of the cap rock	Interpreted seismic horizons	Build 3D basin-scale model
Reservoir properties	From well data and literature	Build 3D basin-scale model
Fault map	Interpreted faults from seismic	Build a 3D model for migration analysis
Fault properties assumptions	Geological model	Build a 3D model for migration analysis
Licence block boundaries	Map data	To check if migration paths will conflict with other interests
Existing hydrocarbon fields	Map data	To check if migration paths will conflict with other interests
Surface infrastructure	Map data	To check if migration paths will conflict with other interests
Well tops	Interpreted well logs	Construction of 3D geological model
Tectonic setting/tectonic regime	From literature	Likelihood of fault reactivation

7.6.3 Input from other workflow elements

The main input from other workflows are a basine-scale, 3D model of the reservoir and seal rosk with interpreted faults included and, if possible, fault properties from geomechanical analysis. In addition, access to plume migration modelling would be useful; if not available basin modelling should be carried out in the migration path analysis. An overview of possible spill points from top reservoir surface should be gained either from static storage site modelling or from basin–scale modelling. See Table 7.18 for a summary.

Old wells are critical points for possible leakage. For instance an old well can have been plugged at the bottom, but if the CO_2 gas migrates into the well at shallower depths, well integrity at that level becomes a concern. Such analysis should be carried out in the well integrity study and should be used as input into the migration path analysis.

Table 7.18 Input data for migration path analysis from other workflow elements.

Input	**Source**	**Usage**
Fault properties	Geomechanical modelling	Input to evaluate leakage risk
Weak points of wells	Well integrity study	Possible leakage from wells
3D static model/3D basin seal and reservoir model + faults	Static model	Build a 3D model for migration analysis
Plume migration	Dynamic modelling	Analyse possible leakage path(s)
Spill points from top reservoir surface	Static modelling	Analyse possible leakage path(s)

7.6.4 Results

Table 7.19 lists the output of this part of the workflow, which includes a migration and leakage model that enables estimating the areal and vertical extent of injected CO_2, migration path ways, flux rate of the migration, most likely leakage paths (*e.g.*, faults or old wells). The probability of leakage from the storage site should also be quantified.

The result from this workflow can be compared with output from reservoir modelling.

7.6.5 Links with other workflow elements

The migration path analysis requires input from static models, *e.g.*, a 3D fault and fracture framework to characterise the fracture system. It also needs input from well integrity with regard to the weak points and leakage pathways in wells, and input from dynamic modelling on the position of injected CO_2 over time. The migration path analysis produces stronger results if quantitative risks assessment is included.

7.6.6 Uncertainties and risk factors

A key issue that migration path analysis aims to address is to the extent to which the injected CO_2 migrates away from the injection sites(s), in terms of both distance and time. It is therefore important to evaluate whether the migration will interfere with other subsurface applications, such as hydrocarbon field exploration and exploitation. In addition, if the assumed projected storage structure is close to country borders, it is important to assess potential migration across these borders. Other areas of potential interference are surface installations and potable water bearing aquifers affected by migration and potential leakage out of the storage site. Therefore, it is also important to evaluate whether the expected migration path will be close to assumed open wells or fault zones.

Table 7.19 Results from migration path analysis.

Result	Description	Usage
Properties for leakage points		Fracture system characterisation and man-made pathways
Migration leakage model		The rate of migration (in open-ended reservoirs). This can be used as input in the dynamic modelling
Brine displacement		Areal and vertical extent of the effect of CO_2 vs. time. Can be used further in dynamic modelling
Probability estimated for leakage	Quantify uncertainties in input parameter and probability of migration path ways and risk of leakage	The risk of leakage from the storage site
Evaluation of sealing faults and possible new faults		Fracture sealing rates

7.6.7 Key concerns

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

7.7 Socio-geographic analysis

Although a socio-geographic analysis is not part of a site characterisation according to the EU storage directive, it is included here for completeness, as it is an integral part of the site characterisation as performed in the SiteChar project.

7.7.1 Description of tasks

The social site characterisation performed in the SiteChar project has the following four elements:

- Social site characterisation. This step consists of desk research, stakeholder interviews, media analysis and an first survey among representatives of the local community. The aim in this step is to identify the stakeholders and to determine the factors that drive perceptions of and attitudes towards CCS.
- Focus conferences. A key element of the work was the use of focus conferences, a new format of public outreach that involves at once project operators, authorities and the local public. Focus conferences organised in the SiteChar project typically lasted two days and were repeated once with at most one month. In the setup of the conferences, particular emphasis was given to providing knowledge, allowing space for open discussions, allowing participants to gain their own experiences and creating opportunities to compare their opinion with that of others.
- Information dissemination. Generic as well as site specific information on CCS is made available to the general and local public. Web-based information is provided and public information meetings are organised.
- Repeat survey. A second survey of public awareness is performed, among a new group of representatives of the local community. Changes in awareness, knowledge and opinions of CCS over time can be monitored. In addition, the repeat survey can be used to validate and quantify the findings from the focus conferences.

7.7.2 Input

The EU Directive Aspects can be found in

- Aarhus convention and related documents1;
- Directive 2009/31/EC: Public access to environmental information;
- Directive 2003/35/EC: Public participation in environmental decision-making.

Data to be obtained for social site characterisation include (Table 7.20):

- Population density & other sociodemographic data.
- Area characteristics *e.g.* history, culture.
- Pressing issues in area (*e.g.* other industrial projects).
- National context (*e.g.* regulatory).
- Relevant stakeholders.
- Existing hydrocarbon fields, Natura 2000 areas .
- Information about the area, *e.g.*, relevant stakeholders in the area.
- Generic information on CCS in the country where the project takes place.

[1] http://ec.europa.eu/environment/aarhus/

Table 7.20 Input data for socio-geographic analysis.

Data	Source	Usage
Desk research data	Various, *e.g.*, EU directives	Social site characterisation
Interview data	Local stakeholders	Social site characterisation
Media analysis data	Local newspapers	Social site characterisation

7.7.3 Input from other workflow elements

For the public outreach activities, input from the geologically and engineering oriented disciplines is required regarding the timing of decisions and activities in the project. Where those activities have an impact on the local environment, such as seismic data acquisition, baseline data measurement, drilling activities, this should be made available to the socio-geographics team.

Table 7.21 Input data for sociogeographic analysis from other workflow elements.

Input	Source	Usage
Technical site characteristics	All elements of technical and economical characterisation, their timing and possible impact on the local environment	Information dissemination

7.7.4 Results

The results of the socio-geographic analysis will be input for the risk analysis. The results are obtained from a qualitative and quantitative social site characterisation: a detailed description of the local area in terms of population characteristics, developments that are perceived relevant by the local public, present views on CCS, questions and concerns about CCS.

The surveys show that public awareness and perceptions of local plans for CCS can be measured reliably without alarming/frightening people upfront that something in their area may happen, and without encouraging them to develop opinions that have no base in awareness or knowledge of any plans.

The focus conference method is suitable for raising public awareness and to assist public opinion formation about complex issues such as CCS. Moreover, the method can be used to initiate local discussion and planning processes together with the local community in a balanced, informed way.

7.7.5 Links with other workflow elements

Progress or outcomes of technical site characterisation are to be shared with the local general public in public outreach activities, to create understanding in the public of the efforts made to ensure secure storage of CO_2.

7.7.6 Uncertainties and risk factors

The main threat to social site assessment is uncoordinated public action, when the intention to develop a CCS project at some specific site is made public by other parties. Examples of identified risks related to technical site characterisation are the following (list is not exhaustive):

- Restrictions to surface installations;
- Environmental protected areas;
- Lac of political support;
- Lack of public acceptance;

- Competition with other uses of the subsurface, such as hydrocarbon field exploration or production, natural gas storage or geothermal energy projects;
- Lack of cooperation from the local community to approve land use by the project;
- Owner of store site does not agree to use or change of use;
- Inadequate access to the site.

7.7.7 Key concerns

In order to obtain constructive focus conferences, the following is key:

- Independent facilitators should organise the focus conferences.
- Ensure trust in the facilitators and allow time to create a safe environment.
- Embed focus conferences in a range of public engagement activities.
- Do not extrapolate findings from small group research to communities (rather, use surveys).
- Balance positions taken by speakers and in discussion materials.
- In real CCS projects, efforts in social site characterisation, information dissemination and raising public awareness, as well as their outcomes, should be embedded in the overall project activities. The relation with national policy agendas and priorities should be clarified.

8 SITE CHARACTERISATION (4): Monitoring and Mitigation plans; development plan and economics

8.1 Monitoring plans

Site characterisation seeks to reduce uncertainties and associated risks in a storage operation. However, it is likely that some uncertainties and residual risks will remain following detailed site characterisation, well design and construction of the storage development plan. A monitoring plan is designed to monitor and reduce these uncertainties in the storage project and as such is designed to specifically address the residual site-specific risks identified during risk assessments. The principle objectives of the monitoring plan can be summarized as determining whether

- injected CO_2 is behaving as expected;
- any unexpected migration or leakage occurs;
- any identified leakage is a threat to the environment or human health.

The monitoring plan should be flexible, adapting to changing and reducing uncertainties as the project continues and an increasing volume of data is acquired.

8.1.1 Developing a monitoring plan

Key stages in developing a monitoring plan are the following:

1. Select a potential site and undertake preliminary site characterisation.
2. Identify risks to the storage and assess their impact on the storage site.
   Assessing risks might include: leakage mechanisms such as wells, cap rock and/or fault-controlled leakage. Issues to consider include: likely pathways, potential concentrations and fluxes, receptor domains and potential impacts.
3. Undertake further (exploratory) characterisation work to reduce uncertainties in understanding the site.
4. Perform reservoir modelling to predict site performance.
5. Design an injection programme and the injection infrastructure.
6. Define monitoring domains, *e.g.*, storage complex, wells, reservoir, overburden aquifer, and surface.
7. Identify key parameters to monitor, to reduce risks that are not mitigated by preventative measures.
8. Develop a monitoring plan. Issues to consider include:
   a. Objectives
   b. Parameters to be measured – detection limits, the uses to which data will be put.
   c. Technology selection – justification will include performance (detection limits, reliability), technology maturity, costs (of deployment, maintenance, data interpretation), footprint of area monitored.
   d. Timing – continuous monitoring, frequency and timing of periodic monitoring activities.
   e. Link between monitoring data and site performance modelling (reservoir/plume behaviour, risk assessment, containment).
   f. Reporting.

9. Conduct a baseline survey for monitoring prior to injection – for environmental impact assessment, reservoir performance.

10. Monitoring during injection. This will be split into two categories:
    a. Monitoring needed to establish site operational performance;
    b. Monitoring needed if a 'significant irregularity' or 'leakage' (as defined in the Storage Directive) is detected.

11. Revise reservoir models and assess new risk profile, following measurement of monitoring data.

12. Revise monitoring plan if needed.

13. Following the end of the injection period, monitoring will continue to establish that the site performance is likely to lead to permanent containment and that no leakage is expected. The Storage Directive indicates this might be for a period of twenty years, but the Competent Authorities may shorten this period if they are convinced that the operator has given proof for complete and permanent containment as requested in Art.18.1a of the EU Storage Directive.

8.2 Corrective measures plan

The operator of a site has to take corrective measures in case of leakages or significant irregularities. This is stipulated in Art. 16 of the EU Storage Directive. In connection with this obligation the operator has to propose a corrective measures plan according to art. 7 of the EU Storage Directive, upon applying for a storage permit. This plan has to be approved of by the CA before a storage permit is granted according to Art. 8 of the Storage Directive. The EU Storage Directive does provide specifications for the corrective measures plan or how to produce it.

8.3 Key concerns

- Risk Assessment is key for the monitoring plan. As noted in section 8.1.1 above, the risk assessment guides the site characterisation, as well as the design of the monitoring plan.
- Feasibility studies on new, low-cost, efficient monitoring techniques are needed, to describe the cost-benefit and efficacy of new monitoring methods. This certainly holds for areas with the highest residual risk.
- Baseline studies must be performed to ensure that enough pre-injection background data are collected.

The Storage Directive does not explicitly require the operator to produce a development plan. Nevertheless it is wise to construct it and to do some economic forecasts on the costs of the storage project. The monitoring plan is an important input in this respect, as technical as well as financial provisions must be made to be able to perform this monitoring, as required in the Storage Directive.

8.4 Site development plan

When the site characterisation study finds no obstacles to secure storage of CO_2, a detailed estimate can be made of the work required for developing the site for storage, as well as of the cost of storage. On the basis of the injection strategy defined in the site characterisation study elements (notably dynamic modelling) and knowledge of existing installations (if any), the effort of developing the site for CO_2 injection can be defined: this constitutes the site development plan.

The site development plan includes information on the key risks at each step along the process and the go / no-go decisions involved. The development plan contains a number of decision gates, at which the project is evaluated and a decision has to be made to enter the next phase in the site development plan.

8.4.1 Timeline overview

Table 8.1 displays a concise overview of different steps involved in the conversion of the installations of a hypothetical depleted gas field. The table also provides an estimate of the duration of each of the steps. It is important to realize that indications of timing are variable and strongly site dependent. The duration of such tasks as workovers of wells and modification of platform(s) depends on the number of wells involved and the type of site or platform. The task duration given in the table is indicative. It is assumed that the staff necessary to do the work is available on demand during the indicated time frames. The activities as well as the timeline will be quite different for a virgin aquifer, with no existing installations or wells.

Table 8.1, together with the timeline shown in Figure 8.1, sketches the steps towards developing a depleted gas field from several years prior to the end of production to start of CO_2 injection. The timeline assumes that several of the activities can be performed in parallel. The workflow assumes that the existing installations can be re-used and / or converted from production to injection.

The site development is broken up into three phases. The decision gates associated with these phases involve increasingly higher budgets. At each decision gate, the level of knowledge about the risks associated with re-use and conversion is improved and the uncertainties are smaller. The budgets mentioned apply to a location in the shallow parts of the North Sea and represent the estimated cost level in 2012.

DG0 This is the decision to start a feasibility study, following selection of the site after a screening study. The budget to be decided on is about 1 M€.

Phase 1 The first phase typically takes one half to one full year, depending on the size of the field.

DG1 This decision concerns the start of the pre-FEED (Front-End Engineering and Design) phase. The budget to be decided on is in the range of 1 – 2 M€.

Phase 2 The second phase takes typically about two years and contains the pre-FEED phase, an Environmental Impact Assessment and licence applications.

DG2 A second decision gate occurs when a detailed cost and timing estimate of the site (re-) development is available. The budget to be decided is of the order of several tens of million euros and strongly depends on the extent of activities.

Phase 3 The third phase concerns detailed engineering, procurement and construction and takes several years.

Comparison with saline formations

The workflows for saline formations and depleted gas fields are similar. Where the starting point for saline formations can be characterized by large uncertainties about the quality of the storage site and a general lack of site and reservoir specific data, the production history of the gas field has resulted in a good knowledge of the reservoir. A large part of the workflow for saline formations is aimed at reaching the level of knowledge and confidence comparable to that for hydrocarbon fields.

Table 8.1 Time table overview for converting a hydrocarbon field to a CO_2storage site. Duration is indicative and based on a hypothetical offshore gas field, Costs given apply to a location in the shallow parts of the North Sea, and are relative to 2012 cost levels (after Neele et al., 2012). It is assumed that a team of specialists works full time for the suggested duration.

	Activity	*Time needed (includes lead times, if any)*	*Comment*
Decision gate DG0: 0.5 – 1 M€			
Phase 1	1. Site characterisation study	0.5 – 1 years	Time and budget depend on size of field Cost estimate ±40-50%
Decision gate DG1: 1 – 2 M€			
Phase 2	2. Environmental impact assessment (EIA)	1 years	More detailed cost estimate, using results from feasibility study Cost estimate ±20%
	3. Pre-FEED (Front-End Engineering and Design)	1 years	Cost estimate ±15%
Decision gate DG2: tens of millions of €			
Phase 3	4. FEED	1 year	Licence approval takes 1 – 2 yrs; activities can continue in parallel
	5. Well workovers	1 – 2 years	In parallel with license application procedure
	6. Platform modifications	1 – 2 year	Parallel to previous item
	7. Pipeline construction	1 year	Costs for high-pressure CO_2 pipeline; in parallel to other construction
	Total	**6 years**	Small platform, 2 wells, no compression on platform; pipeline costs not included

Figure 8.1 illustrates and aligns the development timelines for saline formations and gas fields. It is assumed that 7 years are required for development of a saline formation and 6 years for a gas field. The three phases in the workflow are indicated by the different shades of blue; vertical black lines represent the decision gates. The heavy red vertical line represents the second decision gate in the saline formation study, and the first decision gate in the gas field study. At these milestones in the development, the results for the saline formation can be compared with those for the depleted gas field. In other words, when a proper comparison is to be made between storage in saline formations and in depleted gas fields, the studies must (at least) be at these milestones.

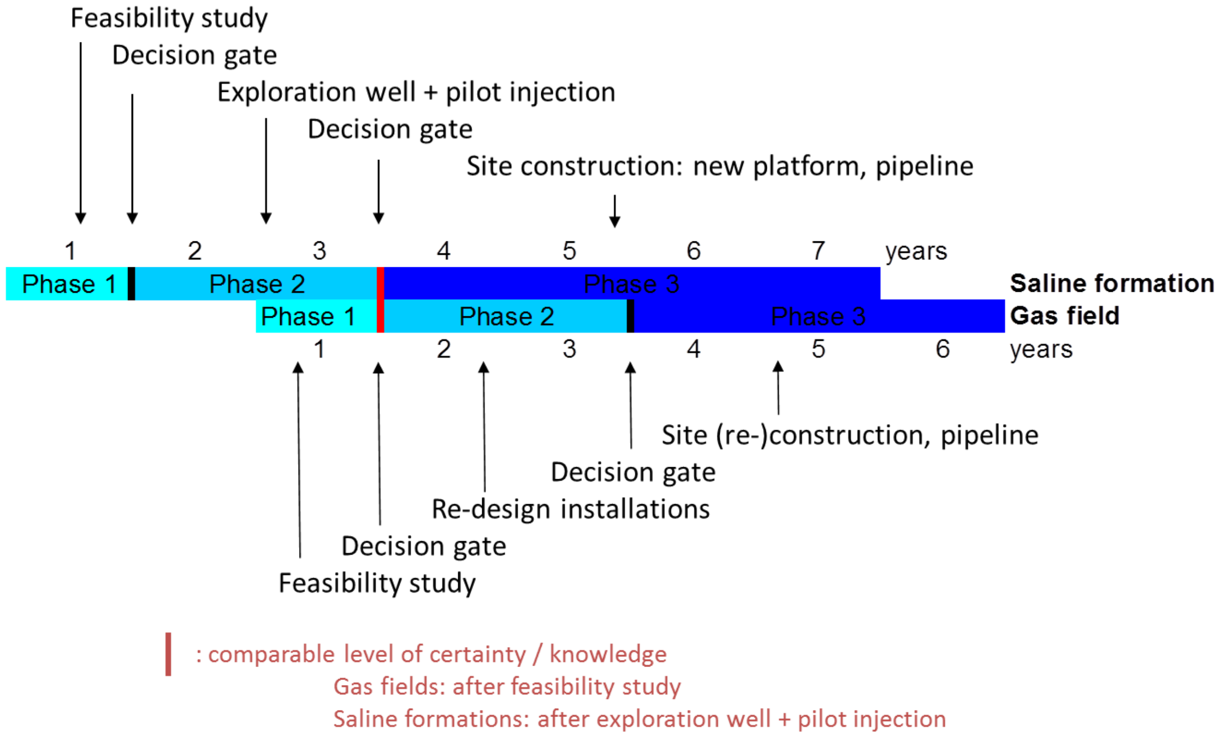

Figure 8.1 Storage site development timelines, for a depleted gas field (lower part of the graph) and a deep saline formation (upper part of the graph). The phases and decision gates are those discussed in the text (after Neele et al., 2012).

8.4.2 High-level storage cost estimate

One of the final steps in a site characterisation study is the assessment of project development costs. The cost of storage is one of the key performance indicators, on the basis of which different storage options can be compared –Capture and Transport will come into the equation as well. Cost indicators include such parameters as the Net Present Value (NPV), total investment cost (CAPEX), operational cost (OPEX), and the unit cost of storage (in terms of €/t CO_2 stored).

In a CO_2 storage project, different phases can be discerned. Generally, investments are required to move from one phase to the next. A brief overview of typical activities is shown in Table 8.2. The geological properties of the reservoir and the required storage rate determine the timing of the transition from one phase to the next. The dynamic modelling activities (section 7.2) result in an estimate of the storage capacity, the number of wells required during the injection to accommodate the CO_2 supply rate and the duration of the injection phase. These results define the distribution of the costs over time, which in turn determines the NPV.

The NPV is computed from the cash flow over time, with cash flow given by the investments and operational costs in the project. If *c(t)* is the cash flow, and *d* the discount factor, the *NPV* is given by expression:

$$NPV = \sum \frac{c(t)}{(1+d)^{t-1}} \qquad (8.1)$$

where the summation is over the duration of the injection project, from preparation to abandonment. The cash flow in this expression can contain only cost (CAPEX, investments and

OPEX, operational costs), but it can also include revenues, for example from a storage fee. If revenues are included, the discount factor that results in an NPV of zero is known as the Internal Rate of Return (IRR).

If the revenue side of the cash flow is made explicit, an approximate storage fee f, or break-even wellhead price, can be computed. The same expression can be used, by defining the required IRR and computing the wellhead CO_2 price that results in an NPV of zero. This involves solving for *f*:

$$\sum \frac{q(t)f - c(t) - r(t)}{(1+IRR)^{t-1}} = 0 \qquad (8.2)$$

where *q(t)* is the storage rate*, c(t)* includes CAPEX and OPEX and *r(t)* represents tax. In this expression, IRR is inserted as the discount rate. Asset depreciation can be included in the tax regime, by deducting these from the taxable income that is the basis for the computation of *r(t).*

Table 8.2 Overview of different phases, activities and cost elements in a CO_2 storage project in a depleted gas field or a saline formation.

Phase	**Activities**	**Investments**
Depleted gas fields:		
Production	Production of natural gas	(None associated with CCS)
End of production	Closing-in of wells, prepare installations for mothballing	mothballing costs
Mothballing	Low-level maintenance	Maintenance
Conversion	Convert existing hardware from production to injection	Platform refurbishment, pumps, heaters, well workovers, pipeline workover or construction
Saline formations:		
Construction	Construct platform(s), drill wells, construct pipeline	Platform, wells, pipeline
Depleted gas fields, saline formations:		
Injection	Injection of CO_2 in reservoir; if applicable, bringing on line or drilling additional wells	Maintenance costs; if applicable, investments to increase or maintain injection rate capacity
End of injection	Closing in of wells	Removal of (some) equipment; preparation of installations for post-injection phase
Post-injection	Monitoring	Maintenance costs, but lower than during injection phase
Abandonment and handover	Remove platform, abandon wells	Abandonment costs

8.4.3 Key concerns

- Developing a site development plan is a key element of site characterisation, as costs will be one of the factors controlling the feasibility of storage.
- Site development must be considered throughout the project taking into account ways to reduce costs starting from an initial estimate of cost levels. A major difficulty might be that economic factors may change significantly during the project.
- Cost data are often rather vague, hard to come by and quickly out of date.

9 Conclusion

This report describes the workflow for a site characterisation study, as required to satisfy the permit requirements as described in the EU Storage Directive (EU, 2009). The current document maps out a general route, but certainly does not describe a process that can be routinely followed.

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. Two parties are directly involved: the operator of the prospective site and the so-called Competent Authorities (CA). Next to the *formal* moments of contact between them, as indicated by the Storage Directive, *it is necessary that the parties have regular contact*. These contacts will inform the operator of what is expected from him in the study, on the basis of the national implementation of the EU Storage Directive. They must also lead to a fuller understanding of the prospective site by the CA, who is 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 involved defines risks and associated adverse scenarios and the work should always be based on the risk assessment and risk ranking. Here again the informal contacts with the CA are a practical necessity. The detailed site characterisation, numerical in nature, may uncover new risks that were not anticipated earlier. These risks must lead to reiteration. It is advisable that parties involved agree on a protocol to be followed in such cases.
3. The characterisation study is multi-disciplinary. It should encompass a *quick scan, qualitative risk assessment, static modelling, dynamic modelling, geochemical analyses and modelling, geomechanical modelling, well integrity analysis, migration path analysis, socio-geographic analysis and quantitative risk analysis.* These phases have been described in this report, with special emphasis on the links between the disciplines. It must be stressed that the focus of the activities in each discipline are strongly *site specific* and should be based on the risk assessment.
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**”. In the characterisation process one has to deal with risks that are specific to the prospective site. This makes it difficult to specify all the actions to be undertaken by the investigators as if they are carved in stone: they are not. This is also partly due to the abstract phraseology in the EU Storage Directive, where terms like “significant risk of leakage” (Art. 4 sub 4) must be operationalized somehow by the national CA.

For these reasons, regular communication between 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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Appendix I: EU Storage Directive

This appendix discusses the links between the EU Storage Directive (EUSD) and the site characterisation elements workflow. Annex II of the EUSD is used here as a reference. It consists of three steps, each being a list of items. These three steps are discussed here, addressing each list item: **which part or parts of the workflow element output is or are required to address / answer it. Any additional work needed to combine or interpret workflow element outputs is to be described.**

The Guidance Documents (EU, 2011) provide an explanation of the list elements.

Data collection (step 1)

	Elements in step 1	Workflow element(s)	Comments
(a)	Geology and geophysics	7.1, 7.2	Many data will come from the hydrocarbon industry (produced gas fields) and must be compiled in the screening phase. In the case of aquifers data might be scarce.
(b)	Hydrogeology (in particular existence of ground water intended for consumption)	7.4	
(c)	Reservoir engineering (including volumetric calculations of pore volume for CO_2 injection and ultimate storage capacity)	7.2	Data must come from the hydrocarbon industry. In case of aquifers the paucity of data is a major problem.
(d)	Geochemistry (dissolution rates, mineralisation rates)	7.4	
(e)	Geomechanics (permeability, fracture pressure)	7.3	Lab experiments necessary.
(f)	Seismicity	3, 7.7	Historic data
(g)	Presence and condition of natural and man-made pathways, including wells and boreholes which could provide leakage pathways	3	Data from hydrocarbon industry
(h)	Domains surrounding the storage complex that may be affected by the storage of CO_2 in the storage site	3	
(i)	Population distribution in the region overlying the storage site	7.7	
(j)	Proximity to valuable natural resources (including in particular Natura 2000 areas pursuant to Council Directive 79/409/EEC of 2 April 1979 on the conservation of wild birds(1) and Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora(2), potable groundwater and hydrocarbons)	3, 7.7	
(k)	Activities around the storage complex and possible interactions with these activities (for	3, 7.7	

	example, exploration, production and storage of hydrocarbons, geothermal use of aquifers and use of underground water reserves)		
(l)	Proximity to the potential CO_2 source(s) (including estimates of the total potential mass of CO_2 economically available for storage) and adequate transport networks	3, 7.7	

Building the 3-D static geological earth model (step 2)

	Elements in step 2	Workflow element(s)	Comments
(a)	Geological structure of the physical trap	7.1	Any model starts with available data and geological background knowledge.
(b)	Geomechanical, geochemical and flow properties of the reservoir overburden (cap rock, seals, porous and permeable horizons) and surrounding formations	7.2, 7.3, 7.4, 7.6	The initial static model(s) is(are) a first best estimate. Feedback loops are to be expected!
(c)	Fracture system characterisation and presence of any human-made pathways	7.1, 7.3, 7.5	
(d)	Areal and vertical extent of the storage complex	7.1, 7.2, 7.6	The migration pathway research validates or updates geological “suspicions” in 7.1
(e)	Pore space volume (including porosity distribution)	7.1, 7.2	To come from reservoir dynamic modelling
(f)	Baseline fluid distribution	7.1	Data from the hydrocarbon industry are basic ingredients.
(g)	Any other relevant characteristics		
(all)	The uncertainty associated with each of the parameters used to build the model shall be assessed by developing a range of scenarios for each parameter and calculating the appropriate confidence limits. Any uncertainty associated with the model itself shall also be assessed.		1) Uncertainties in *model outline* can be tackled by constructing several models. 2) Uncertainties in the parameters start a priori in the qualitative assessment. Here too the other phases do the updating!

Characterisation of storage dynamic behaviour, sensitivity characterisation, risk assessment (step 3)

Step 3 consists of several parts, which are discussed separately.

Characterisation of the storage dynamic behaviour (step 3.1)

	Elements in step 3, characterisation of the storage dynamic behaviour	Workflow element(s)	Comments
(a)	Possible injection rates and CO_2 stream properties	7.2	
(b)	Efficacy of coupled process modelling (that is, the way various single effects in the simulator(s) interact)	7.1 through 7.6	True coupled modelling is seldom necessary, but may occur in dynamical and geomechanical modelling. Effectively, coupled modelling is implemented through the multiple interactions between the technical disciplines.
(c)	Reactive processes (that is, the way reactions of the injected CO_2 with in situ minerals feedback in the model)	7.4	
(d)	Reservoir simulator used (multiple simulations may be required in order to validate certain findings)	7.2	Any 3D-simulator that has a built-in PVT package that describes CO_2 phases accurately The simulator should treat advection and solubility.
(e)	Short and long-term simulations (to establish CO_2 fate and behaviour over decades and millennia, including the rate of dissolution of CO_2 in water)	7.2, 7.4	One may assume that once the storage site is filled and has come to a position of stability, geochemistry is a stand-alone part of long-term changes. For the injection phase a combination is necessary. Everything depends on the timescales to reach mechanical and thermodynamic equilibrium responses.

Insights from dynamic modelling (step 3.1)

	Elements in step 3, insights from dynamic modelling	Workflow element(s)	Comments
(f)	Pressure and temperature of the storage formation as a function of injection rate and accumulative injection amount over time	7.2	
(g)	Areal and vertical extent of CO_2 vs time	7.2, 7.6	
(h)	Nature of CO_2 flow in the reservoir, including phase behaviour	7.2	The PVT characteristics employed in the reservoir simulator should be openly known.
(i)	CO_2 trapping mechanisms and rates (including spill points and lateral and vertical seals)	3, 7.2, 7.6	The static model already directs the research. Beware!

(j)	Secondary containment systems in the overall storage complex	3, 7.1, 7.2, 7.6	
(k)	Storage capacity and pressure gradients in the storage site	7.2	
(l)	Risk of fracturing the storage formation(s) and cap rock	7.3, 7.5	Geochemical samples may give clues as to the minerals in the seal
(m)	Risk of CO_2 entry into the cap rock	7.3, 7.5	
(n)	Risk of leakage from the storage site (for example, through abandoned or inadequately sealed wells)	7.2, 7.3, 7.5	
(o)	Rate of migration (in open-ended reservoirs)	7.2	
(p)	Fracture sealing rates[2]	7.3, 7.4	Combination of chemical reactions and geomechanical processes
(q)	Changes in formation(s) fluid chemistry and subsequent reactions (for example, pH change, mineral formation) and inclusion of reactive modelling to assess affects	7.2, 7.4	See for the interplay between geochemistry and flow: Step 3.1e
(r)	Displacement of formation fluids	7.2	
(s)	Increased seismicity and elevation of the surface level	7.3	

Sensitivity characterisation (step 3.2)

This element of the EU Storage Directive reads: "*Multiple simulations shall be undertaken to identify the sensitivity of the assessment to assumptions made about particular parameters. The simulations shall be based on altering parameters in the static geological earth model(s), and changing rate functions and assumptions in the dynamic modelling exercise. Any significant sensitivity shall be taken into account in the risk assessment*."

See chapters 2.2 and 6 for how the Risk Assessment is to be performed.

Risk assessment: hazard characterisation (step 3.3.1)

This element of the EU Storage Directive reads: "*The hazard characterisation shall cover the full range of potential operating conditions to test the security of the storage complex. Hazard characterisation shall be undertaken by characterising the potential for leakage from the storage complex, as established through dynamic modelling and security characterisation described above. This shall include consideration of* [the items in the table below]. *The hazard*

[2] The EU Guidance Document #2 does not offer an explanation as to the meaning of 'fracture sealing rates'. Here, fracture sealing is assumed to be a combination of chemical reactions (resulting in mineral deposition in injection-induced fractures) and geomechanical processes (resulting in fractures closing).

characterisation shall cover the full range of potential operating conditions to test the security of the storage complex."

	Risk assessment: hazard characterisation (step 3.3.1)	**Workflow element(s)**	**Comments**
(a)	potential leakage pathways	7.1, 7.2, 7.3, 7.5, 7.6	
(b)	potential magnitude of leakage events for identified leakage pathways (flux rates)	7.1, 7.2, 7.3, 7.5, 7.6	Quantitative investigations can yield this result
(c)	critical parameters affecting potential leakage (for example maximum reservoir pressure, maximum injection rate, temperature, sensitivity to various assumptions in the static geological Earth model(s))	7.2	Use of multiple models as described earlier
(d)	secondary effects of storage of CO_2, including displaced formation fluids and new substances created by the storing of CO_2	7.2, 7.4	
(e)	any other factors which could pose a hazard to human health or the environment (for example physical structures associated with the project)	3, 7.7	

Risk assessment: exposure assessment (step 3.3.2)

This element of the EU Storage Directive reads: "*Based on the characteristics of the environment and the distribution and activities of the human population above the storage complex, and the potential behaviour and fate of leaking CO_2 from potential pathways identified under Step 3.3.1."*

The site characterisation study will yield probability density functions for CO_2 fluxes, times, as deemed necessary by experts in HSE research and industrial safety. See 2.4.4 for details.

Risk assessment: effects characterisation (step 3.3.3)

This element of the SDEU reads: "*Based on the sensitivity of particular species, communities or habitats linked to potential leakage events identified under Step 3.3.1. Where relevant it shall include effects of exposure to elevated CO_2 concentrations in the biosphere (including soils, marine sediments and benthic waters (asphyxiation; hypercapnia) and reduced pH in those environments as a consequence of leaking CO_2). It shall also include an assessment of the effects of other substances that may be present in leaking CO_2 streams (either impurities present in the injection stream or new substances formed through storage of CO_2). These effects shall be considered at a range of temporal and spatial scales, and linked to a range of different magnitudes of leakage events."*

Risk assessment: risk characterisation (step 3.3.4)

This element of the EU Storage Directive reads: "*This shall comprise an assessment of the safety and integrity of the site in the short and long term, including an assessment of the risk of leakage under the proposed conditions of use, and of the worst-case environment and health impacts. The risk characterisation shall be conducted based on the hazard, exposure and effects assessment. It shall include an assessment of the sources of uncertainty identified during the steps of characterisation and assessment of storage site and when feasible, a description of the possibilities to reduce uncertainty.*"

The site characterisation study will yield probability density functions for CO_2 fluxes, times, as deemed necessary by experts in HSE research and industrial safety. See 2.4.4 for details.

APPENDIX 2: An auxiliary tool: "Numerical" Qualitative RA.

In qualitative RA risks are highlighted, scenarios proposed and discussed and at such an early stage the output is qualitative in nature. It was realized some time ago that this qualitative RA can still be strengthened by adding some *probabilistic* numerical "experimentation" (Nepveu *et al.*, 2009). The crucial thought is that all kinds of events (E) and processes (P), forming part of the scenarios, can be reformulated as *states* in a dynamic system, together with appropriate combinations (E, P). States can transform into (some) other states and the propensity to do this is described by transition probabilities. There can be various "end states", the ones that represent situations one wishes to avoid. For instance, leaking along wells, leaking through the seal, brine displacement, represent various possible end states in the system. An important point to make is that if one admits that a risk is real such end states will theoretically *eventually* be reached in the dynamic system constructed. The evolution of such a system is now modelled with help of the theory of so-called "absorbing" Markov chains. "Absorbing" is important, as from these states there is no way back to the other (transient) states without explicitly interfering with the system.

Given the transition probabilities one can answer several practically relevant questions:

- How long will it take from a given state to "absorption" into an end state?
- How long (and how often -which is not the same thing) will the system on average reside in each transient state before absorption?
- What are the probabilities to end up in the various end states?

Eliciting transition probabilities directly from experts is difficult in practice, simply because the "comfort zone" of the experts to be elicited is not necessarily that of the probabilist. There is a way to circumvent this problem to some extent: it is possible to "play" with various possibilities and see how they influence the answers. This course of action has two benefits:

1. The exercise may point to critical connections in the system which demand attention, such as the definition in advance of mitigation activities –adding an extra state into the system (!).
2. This exercise delivers the relative probabilities of the various unwanted end states, and may guide (direct) further quantitative work. This last point is important as the amount of uncertainties one has to deal with in site characterisation is always large. Each serious indication that some mishaps are definitely more likely than others may help to define the workload sensibly, putting emphasis where needed.

APPENDIX 3: Risks and Bayesian Probability

In the characterisation and risk assessment business “uncertainty” plays a vital role. In the subsurface some events may happen, some features may exist, but the investigator is not certain of this. Therefore, he can just speak in terms of probability. Consequently, the concept of “probability” intrudes itself in the workflow. Since there are two major concepts of “probability” it is important to dwell on it for a while; confusion in this matter must not be allowed to enter the scientific discourse.

The “ontological” concept of probability is rooted in the world as we experience it.

A die is thrown over and over again and in 1/6 of the cases the ”two” will turn up. One can decide that the probability of the ”two” is 1/6 on account of our experiments. One may see this as a property of the dice, based on long-term behaviour when throwing.” Those who adhere to this probability concept are called “frequentists”. This frequentist concept is usually taught at universities, and the statistics taught there is based on it. In this kind of statistics there is no place for the inclusion of background knowledge.

The “epistemological” concept of probability, on the other hand, is rooted in our knowledge.

We attach a probability to some event a priori and we have to update this probability as new facts, knowledge comes in. Historically, this concept was initiated by Thomas Bayes in the mid-18th century and developed by Pierre-Simon Laplace somewhat later. In the epistemological concept knowledge is an important “driver” for assigning and updating probabilities. If two persons are in two different states of knowledge they will attach different probabilities to the same event. This is the reason that adherents of this probability concept are sometimes called “subjectivists”. Unfortunately the undertones of this word are slightly negative and until the 1970’s there were fierce debates between the two groups. In the meantime the use of epistemological probability is ever more spreading, and certainly in hard scientific disciplines (like astrophysics, geophysics, image enhancing).

It can be rigorously proved that some simple desiderata on what human reasoning is supposed to adhere to, unequivocally lead to Bayesian probability (Jaynes, 2003). The Kolmogorov axioms of frequentist probability hold here as well, but with a far wider meaning. Whereas classical (frequentist) probability has as its objects random variables, Bayesian probability allows to pass a probability on hypotheses too. In fact, statistics as a subject separate from probability theory exists in the frequentist conception, but not with the epistemologists! With them, statistics is just probability theory. This precludes the use of all kinds of ad-hoc approaches found in classical statistics.

Epistemological (Bayesian) probability is more apt for any business that allows processing of serious amounts of knowledge. It is clear, then, that the probability concept we must use in the characterisation and risk assessment is the epistemological one. Probabilities are not carved in stone, but must be updated with advancing knowledge. What we do is consistent with the epistemological stance. The QRA can be interpreted as equivalent to determining the prior probabilities, the numerical work is equivalent to determining likelihoods. The coupling of the two yields the posterior probability as Bayesians call it.

Finally, the concept of “risk” is related to this posterior probability. Loosely speaking risk is the product of likelihood and effect.

Ultimately we are interested in risks, the nature of which has been defined in the qualitative phase. Risk is the product of probability and effect, but let us write it down more formally. Usually, it is assumed that the severity of the effect is a function of some parameters q_1, q_2 etc. Then the risk is defined as

$Risk \equiv \int p(q_1, q_2, \ldots | Data, I) \cdot Effect(q_1, q_2, \ldots)\, dq_1\, dq_2 \ldots\ldots$ (1)

The integration extends over all of parameter space, with the understanding that $Effect(q_1, q_2, \ldots)$ may be zero for parts of the parameter space. In this formula $p(q_1, q_2, \ldots | Data, I)$ is the joint probability density function (pdf) of the parameter values $q_1, q_2, \ldots$ *consequential upon* the data (*Data*) and background knowledge *I*. Bayesians call this impressive animal a *posterior probability*. Hence, risk is the so-called mathematical expectation of the *Effect* over the posterior probability. One important comment is in order: this *posterior* probability is related in a succinct way (Bayes' theorem) to the so-called *prior* probability that we attribute to $Effect(q_1, q_2, \ldots)$ before we have done all kinds of data processing / computational work.

In order to be complete in our description we write down Bayes' theorem in full.

$$p(q_1, q_2, \ldots | Data, I) = p(q_1, q_2 \ldots | I)\, p(Data | q_1, q_2 \ldots, I) / p(Data)$$

with

$$p(Data) = \int p(y_1, y_2, \ldots | I)\, p(Data | y_1, y_2, \ldots, I)\, dy_1\, dy_2 \ldots. \quad (2)$$

where the integration is over all possible values y_j in the high-dimensional parameter space; with the dimensionality equal to the number of parameters.

Our qualitative RA singles out parameters to be important as possessing potential negative "Effect". It is the definition of the *prior* probability – in many cases just a series of (weighted?) delta-functions.

Data is to be interpreted as the results of *quantitative* work. Actually, $Effect(q_1, q_2, \ldots)$ is also determined in the last steps when the results of hazards are computed, for instance the CO_2 fluxes that result from leakage.

To re-iterate, our qualitative phase determines which parameters are to be investigated, but also which ones look sufficiently innocent to be disregarded. This phase sets the scene and drives / guides the subsequent steps. Each of the runs we carry through the various modelling steps represents one point in $(q_1, q_2, \ldots.)$ space.

Lastly, suppose for evaluation of *Effect* we only need the CO_2 flux per square meter at the surface and the time span of such an eruption of CO_2. Then these runs together shape the pdf for the combined parameters "flow/m^2" and "timespan of eruption". If we have covered our parameter spaces in the various previous steps this pdf should be a fair representation of our *state of knowledge.* This state of knowledge now includes both our knowledge of the possible *variability* of all kinds of parameters in space and time and our *limited* a priori knowledge.

The intention of these deliberations is to show that our process of qualitative RA and subsequent quantification is in line with Bayesian principles, and hence trustworthy.

APPENDIX 4: How many models are needed?

It is obviously an important question to ask: how many models are needed for results to be comprehensive? An answer can be found with help of a result by Buckingham in 1914[3] concerning dimensionless numbers.

Dimensionless numbers are vital for describing (and experimenting with) a physical situation. The fact that we can test ships in small water tanks is the result of the fact that only one dimensionless parameter rules its fluid dynamic behavior, namely the Reynoldsnumber that can assume the same value with different combinations of velocity, length and viscosity. In any physical situation we might ask how many dimensionless parameters fully describe the situation. We want a complete set of such variables - not more, not less. How can we determine the number? Buckingham's result (PI-Theorem) gives the answer:

If we describe a physical situation with M physical parameters (pressure, velocity, permeability of layer 1, layer 2, …) *and the total number of basic physical units* (time, length, mass,…) *involved is N, then we can construct a complete set of precisely (M-N) independent dimensionless parameters for the description..*

All we have to do is list all parameters that (seem to) matter in any concrete situation, check which fundamental units are involved, and the theorem gives the result. The theorem does *not* tell which dimensionless numbers are the most meaningful ones; that is up to the scientist to decide. One can now estimate the ranges of the dimensionless numbers in the complete set and hence make an estimate how many runs are needed to describe the system in full. Undoubtedly, this number will be extremely prohibitive in subsurface situations where there are many different layers. It is the scientist's job to weed out those that are unlikely to matter much, and here again communication between operator and CA is crucial if the work is to be completed in a sensible time with sensible modelling efforts.

[3] http://www.math.ntnu.no/~hanche/notes/buckingham/buckingham-a4.pdf