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SiteChar

Characterisation of European CO2 storage

Deliverable N° D1.2
Draft site characterisation workflow

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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)	
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Content

1 Introduction

The large-scale introduction of Carbon Capture and Storage (CCS) 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, 2009). The storage capacity of deep geological formations is largely sufficient to store CO_2 emission for several decades into the future (IEA, 2009), 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). 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 CO_2 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.

This report represents one of the central goals within the SiteChar project: *to develop a workflow for site characterisation studies for the storage of CO_2*. The workflow defines the work to be done to comply with the EU Storage Directive (EU, 2009; see also Section 8.1), resulting in efficient site characterisation studies.

A number of reports have been published that address site characterisation for CO_2 storage (CO2CRC, 2008; DNV, 2009; NETL, 2010; EU, 2011; Neele et al., 2011). These reports point out, to varying degree, the work to be done to include all aspects for a safe and secure geological storage of CO_2 in a specific formation. However, a number of aspects of the site characterization process are not or partly covered:

- The sequence of the different steps and the timing of the process,
- Interdependencies and feedback loops within the process, i.e. which steps require input from which other steps?
- The coverage of the different aspects of the EU Storage Directive in the process.

Improved knowledge on these questions will streamline the site characterization process, and make sure that the output covers all aspects of the EU storage directive.

This report represents a first version of the site characterisation workflow developed within SiteChar. This workflow will be applied in the site characterisation work in the five storage sites studied in the SiteChar project. It is important to note that this workflow is not finalized. It has to be improved and validated. At the end of the project, the experience from the five sites will be incorporated in the final, consolidated version of the workflow.

1.1 Workflow background

This workflow is based on the compilation of previously completed site characterization studies such as the study for the Rotterdam Climate Initiative [*Neele et al., 2011*] for CCS in depleted gasfields off the coast of the Netherlands or the CO2CRC report (2008). The workflow presented in this report is the result of a joint effort by the partners in the SiteChar project and reflects the experience of the partners in performing site characterisation studies.

1.2 Interplay Operator / Competent Authorities

Apart from the technical aspect of defining a workflow there is a very important second issue: the interplay between the operator of a prospective site and the “Competent Authorities”” (CA) as mentioned in the EU Storage Directive. The identity of the operator who will perform a site characterization is clear enough; who the CA are depends on the national laws in force at the site under scrutiny. In the following we assume that it is clear who they are in any concrete situation, and we will call them “CA” collectively.

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 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 operator and CA cannot remain restricted to formal moments in time. The Annexes to the EU Storage Directive show a massive program of research to be conducted, However, in a concrete situation certain parts of the proposed program might be more relevant than others and it has to be decided in an interplay between operator and CA which research is deemed sufficient in order to comply with the requirements of the Storage Directive which requires that a geological formation and its surroundings shall be characterized and assessed as to its suitability for storage. No significant risk of leakage should exist, and no significant environmental or health risk 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 will remain as they are. The continuous interplay, however, will lead to a better understanding of the CA of what the specific characteristics of the proposed site are and what activities to insist on to prepare for a permit application and as conditions of the storage permit. It will also lead to a clearer focus of the operator on what to deliver at the formal moments in the process. Nevertheless, the different roles of operator and CA must remain clear. The informal contacts should always be and remain honest. The operator informs the CA completely and in full sincerity. The CA should ask what is reasonable in the circumstances, given that some of their demands will have a mandatory character on the grounds of legislation.

In the remainder of this report attention will be paid to this interplay and the roles of operator and CA in this process.

2 Workflow

A site characterisation study generally commences with a screening and selection study of the possible 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 (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 qualification of the reservoir, but also the cap rock and the overburden. While in oil and gas exploration the object of study is a proven reservoir, in the case of CO_2 storage the ability of a geological structure to trap and retain CO_2 permanently must be demonstrated. 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:

- 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:

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

The workflow can be separated into two main elements, indicated in orange, and a number of sub-elements, indicated in blue and purple. These elements are indicated briefly below and described in more detail in the sections 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), economical 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 form an opinion on available data and use knowledge of a general nature. 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. We refer to Ramirez et al (2010) for a review in this respect. The expected output of the screening phase is a list of *promising* potential storage sites. It is worthwhile to emphasize that at this stage storage sites can at best be deemed *promising,* The next step, that of characterisation and assessment, is actually meant to either elevate such sites to the status of “suitable”, or dismiss them. Section 3 describes the screening phase in some detail.

2. SITE CHARACTERISATION STUDY (including ASSESSMENT). Any promising site on the shortlist is eligible for the next step, that of ”characterisation”.
    a. The first step in the characterisation study is to collect *all* available data on the site. 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 may 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 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 the data collected are suitable enough to give potential evidence of the storage prospect*. The available data may come from companies, which collected the data with an entirely different goal. For instance, oil companies are hardly 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 container. Hence, the CA should view the data with respect to their completeness for the characterisation and assessment as intended.
    b. The second step is a quick analysis of the available data. The aim of this step is to identify any problems related to the site before the study is continued. In practice, the experts or persons covering the areas of expertise listed above consider all the available data, so as to find anything that could impede safe and secure storage, or that could affect the site’s ability to meet the storage requirements (as described above, under ‘screening study’). See section 4.1.
    c. A qualitative risk assessment has to be engaged as soon as possible during the characterisation phase. The quick analysis is also usually followed by a workshop with the specialists from the team, who define the risks associated with the site. These risks are related to the safety and security of storage, as well as the conformity 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. See section 4.2 for a more extensive description.
    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 series of rectangular blue boxes contained by the yellow rectangle 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 in the team. Sections 4.3 through 4.9 describe in details how storage feasibility is approached in the different areas of expertise. The section pays special attention to the exchange of data and results among the areas and how their results apply to elements of the storage directive.

e. Once all aspects of safe and secure storage, as described in sections 4.3 through 4.9, have been studied and once internal consistency in results and data is reached, the risk analysis can be made quantitative, in a quantitative risk assessment (see section 4.10). Risks are compared to *a priori* determined risk threshold(s). Adequate mitigation action are then envisaged so as to reduce risks. However, if risks are too high and mitigation measures can not be taken or are too expensive, the site shall be discarded. In that case, the whole process can be started again with another site from the shortlist resulting from the screening study.

f. If the risks fall below established threshold(s), e.g. because there is the option of monitoring[1] 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 (section 4.12), drafting a site development plan (section 4.13) and analysing the costs of storage. The monitoring plan is a requirement for a storage site, defined in the storage directive, while the site development plan is part of the activities of the future operator. 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. Hence the iterative process, indicated here by the two arrows.

2.1 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.* 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 an overriding importance. The team must be such that “sensible completeness” can be reached. 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 prominently, 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, which processes unfold. *If and when such new risks show up the characterisation process has to be reiterated*. From a practical stance it might be appropriate to formalize things as well 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 process.

2.2 Basic considerations on Risk Assessment.

Before a proper 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 when, unfortunately, 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 CO2 storage is always interpreted on the basis of HSE. However, for a site operator, economic risk is important and he might like a

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[1] Guidance Document #2 states that the aim of a site characterization should be to “assess the site’s containment, injectivity, capacity, integrity, hydrodynamics, and monitorability in order to ensure safe and sustainable storage of CO_2” (EU-GD, 2011).

risk assessment on this basis as well as on HSE issues. This aspect is usually treated somewhat differently, by financial-economic specialists.]

All Risk Assessment starts with risk identification and qualitative evaluation. This is a crucial phase in risk assessment and 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 we can define a priori might include:

- CO_2 leakage via the seal, 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.

Let us now focus on a practical approach of this matter. 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 likely 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 in the risk assessment proper. 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.

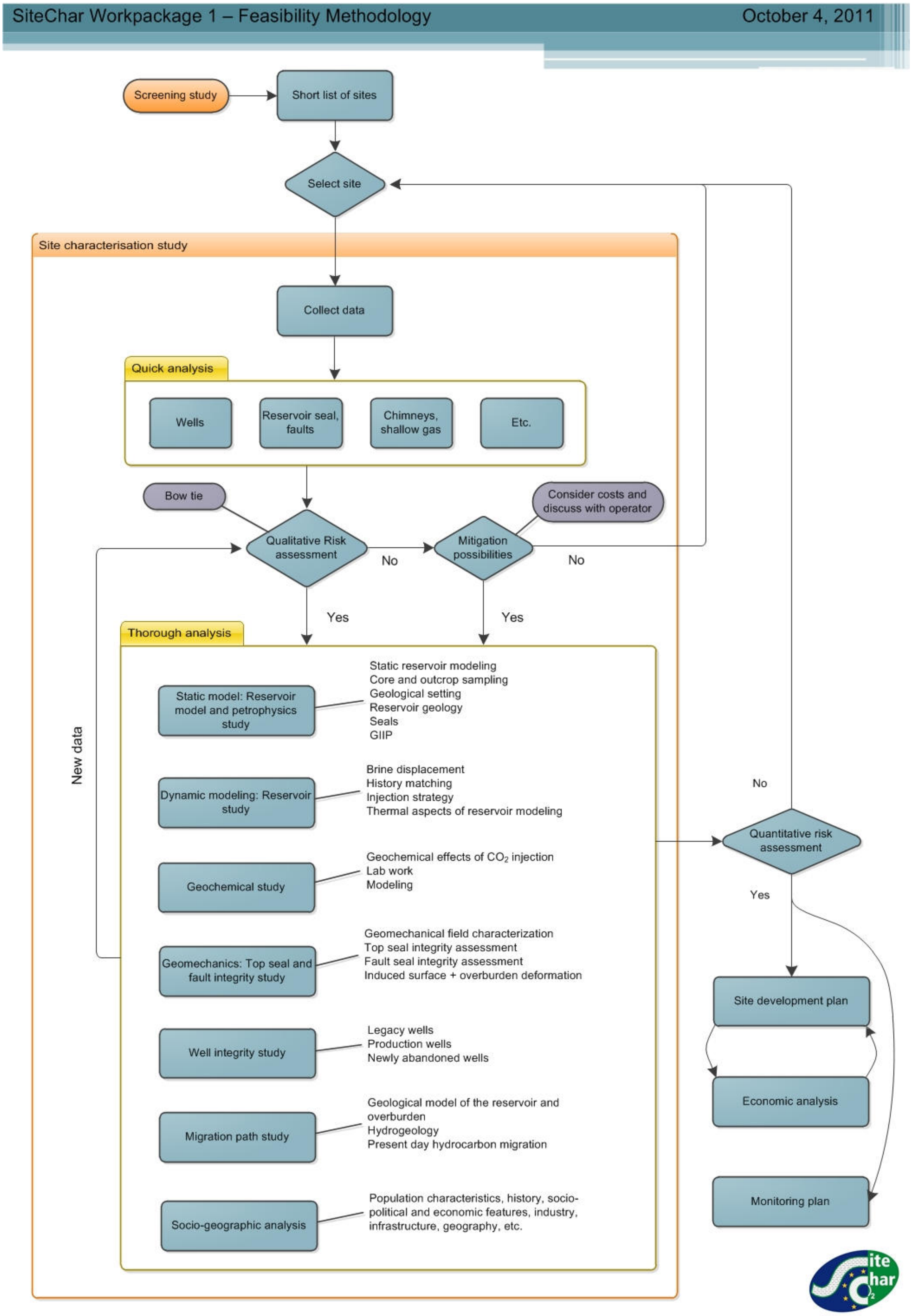

Figure 2.1 – Graphical representation of a site characterisation study workflow. Arrows represent the flow of activities and information; squares represent decision points.

3 Screening study

Any site characterization 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 application, a screening study needs to be performed. First of all criteria must be defined to be fulfilled by the prospective storage site. Obviously, the CA has the lead here. 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 caprock
Seismic 2D and 3D (maps, surveys or segy data)	Map the areal extension 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 CO2 itself could activate quiescent pre-existing tectonic discontinuities and/or create new ones. This could represent preferential pathways for the CO_2 to migrate out of the reservoir, through the caprock, into the overburden and potentially to the surface.

Data	Objective
Seismic hazard maps, Seismic intensity maps, Earthquakes catalogs	Assess the natural seismicity that could affect the storage complex

3) A preliminary estimation must be made of the storage capacity. In this step obviously some assumptions will enter, 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 conflict of interest with other uses of the subsoil (i.e., other activities with economic impact (i.e., water extraction, hydrocarbon production).

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

5) Estimation of the economical 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 and 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 space,
3. Obvious lack of containment potential,
4. Conflict of interest with other economical activities,
5. Seismic and other hazards,
6. Impossibility to monitor adequately

If the verdict is that the site is promising it should also be discussed which data have to be collected not yet present in the available collection. Operator and CA should have intensive (informal) contact over this, so as to enhance the quality and swiftness of the process..

The CA can be expected to pay attention to highly relevant issues concerning available data. Here a list is given of some such high-level questions:

Depleted Hydrocarbon reservoirs

1. Which additional data are needed for a characterization study that has not been acquired for HC production? (e.g. longterm behaviour / far field properties / caprock integrity)

2. Were any data acquired with older technologies? Does it require new acquisition?

3. Are there any changes in reservoir pressure at the last production stages through water influx?

4. What conditions may have changed since last data acquisition? In particular: state of the wells

5. Are there any particular issues (liability / archiving / well description and abandonment conditions)?

Saline Aquifers

1. Since the location is often near (down dip) HC locations, what information do such HC locations provide? Meaningfull for the promising storage site at hand?

2. What are the options for “Migration assisted trapping” by mineralisation, dissolution?

3. Is it possible to use high resolution seismics to map out migration pathways?

4. What about hthe use of correlation of well logs/ cores and high resolution seismics to identify the presence of amplitude anomalies and facies characteristics?

5. What about the variability in seal and reservoir characteristics: how to predict and identify?

6. What about the ability to determine rock properties by core and petrophysical lab assessment? Can we derive something about the efficiency of trap mechanisms?

Conclusion.

The screening study will determine whether there are potentially suitable sites for CO_2 storage within the area of interest. Where there are more than one potentially suitable site, a shortlist will be the outcome from the screening study. This shortlist contains sites that are worthwhile further examination of their potential as a storage location. “Worthwhile” should be interpreted as “*promising* as a storage site”. It is expected that actual experience in many such screening and characterisation trajects 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 characterization study. Which further data should be sought should be discussed between operator and CA under the provisos discussed above. The need for additional data should be made explicit.

In addition, at this stage it is decided whether the conditions to start the site characterization process are present or not, this in order to avoid carrying out failing projects that could damage the CO_2 storage acceptance with respect to both the authorities and citizens. Site characterisation study.

4 Site characterisation study

In this chapter we describe the various elements of a site characterisation study. The organisation of this chapter is as follows.

Section (4.1) treats the so-called quick analysis – intended to quickly eliminate unsuitable sites fast, on the basis of all available data. There is a subsequent need for a qualitative risk analysis, described in section(4.2). This qualitative risk analysis sets the stage for the next steps, described in sections (4.3-9) which are quantitative in nature. The EU Storage Directive describes in the Annexes what the investigation should comprise and the work described in these sections intends to comply with these requirements.

After having detailed the actions involved in these “risk motivated” steps we provide a more abstract overview (4.10) of the requirements and challenges with respect to modelling and numerical treatment.. We add some comments on managing uncertainty. In the subsequent sections (4.11-15) we will describe the *monitoring and mitigation* plan, the site development plan and the high-level cost estimate.

4.1 Quick analysis

In preparation of the qualitative risk assessment (see section 4.2), a quick analysis of the available data is performed. Experts in the different fields of expertise, involved in the site characterization, analyze the data from their viewpoint, by looking at features that present a risk to storage and might compromise storage integrity. These include inter alia the status of the wells which are present in the reservoir, the condition of the reservoir seal and the extent to which faults are present in the reservoir or caprock formations. The presence of chimneys and shallow gas is also considered. The quick analysis is done on all available data that have been obtained after 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 safe and secure storage, or that could affect the site's ability to meet the storage requirements (as described above, 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 characterization process is terminated. In the second case, the results of the quick analysis represent the input to the qualitative risk assessment (section 4.2). The quick analysis does not, by itself, lead to hard decisions regarding the site characterization 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 – if any.

4.2 Qualitative Risk Assessment

4.2.1 Description of task

The activity of site characterization has to be intimately linked with Risk Assessment (henceforth called RA). This follows from the EU Storage Directive, article 4 sub 3 and 4 - this Directive is supposed 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. Risk Assessment will eventually lead to quantitative work, described in more detail in section 4.10. The basis of this work described in the current section, however, is an inventory of the potential aspects and uncertainties deemed relevant for the proposed storage site under scrutiny. The process of obtaining such an inventory is called *Qualitative* RA (henceforth called QRA).

4.2.2 The process; input.

The typical starting point of a QRA (Qualitative Risk Assessment) 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 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 following questions are typical output from the QRA process:

- 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 characterization process?
- Which uncertainties are truly essential, so as to influence the (burden of) quantitative treatment by way of modeling?
- Should we abandon the current site 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 the QRA is not aimed just at producing guidelines for follow-up work. QRA 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 should be invited to play an active role in the process.

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 before a round table meeting. This last phase 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 QRA 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 modeling phase, when their evolution is followed and put to a numerical test.

The formal process of QRA is a necessary step in a formal RA process. During the follow-up steps, when more data are acquired and modeling is underway, a better understanding of the proposed site will ensue. As a result new risks may be discovered, hitherto neglected or deemed irrelevant. Such a discovery might lead to renewed QRA activity. This may take place in the formal way previously described. The main point is that the new insights should be made to affect the site characterization process and quantitative RA. This shows that site characterization is not necessarily a linear process: intertwining of different parts is quite possible, and sometimes truly necessary.

During the entire site characterization work, a risk inventory should be maintained. 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 characterization work should be adapted to reflect a change in insight in the perceived risks.

4.2.3 An auxiliary tool: “Numerical” QRA.

QRA is qualitative. Possible 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 QRA can still be strengthened in this phase 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 modeled with the theory of so-called “absorbing” Markov chains. 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 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, and far from trivial. There is a way to largely circumvent this problem. As a result 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 of mitigation activities –an extra state in the system (!).
2. This exercise delivers the relative probabilities of the various unwanted end states, and may guide (direct) further (quantitative) RA. This last point is important as the amount of uncertainties one has to deal with in site characterization is always large. Each serious indication that some mishaps are definitely more likely than others may structure the workload more sensibly.

4.2.4 Expectations and output from the QRA

1. QRA will point to potential risks during and after the storage activities of the proposed site. The results should be site-specific.

2. QRA may point to major uncertainties and suggest further data collection in specific domains.
3. QRA may help in gaining public acceptance when NGO’s are explicitly invited to take part. In fact, this is the only stage in the site characterization and RA process that lends itself to some sort of participation by “relative” outsiders.
4. QRA will form the basic understanding for negotiations between the CA’s and the groups that perform the site characterization including discussions leading to agreement of site performance indicators. This is a practical necessity as the Storage Directive in its Annexes produces a complete portfolio of research activities that may well be more than is required for a given site. In the negotiations it should become clear which aspects of the site characterization require scrutiny and to which extent they do.

4.3 Static model building

4.3.1 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 is done by creating a 'static' structural geological model or Earth model of the storage complex. Prior the construction of this model, discussions between experts in geology, flow simulation and other fields of expertise must take place to agree the purpose of the model, capacity estimation, flow simulation& This should lead to a general understanding of the degree of detail required of the geological model for the subsequent steps. This model will be updated according to the results of the site characterization and from discussions between experts.

The different steps in the construction of the model are the following. Building surfaces either in seismic two-way-travel time or depth is the first step for understanding the extent and the geometric characterisation of the geological complex. These surfaces are then incorporated in a 3D structured model that shows the spatial extent of both reservoir and cap rock. The model is then populated with reservoir related properties log data and attributes. This system is called a *static model*, which is the input for a simulation work flow. Such models are built using a range of different types of software, but generally they work following the same procedures. Static modelling may require more than just 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 is dangerous as the model may turn out *seriously wrong*. The number of models used should then reflect the number of geological solutions that adequately reflect the available data and related uncertainties. Diffierent 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).

4.3.2 Input

Several elements and parameters are needed to build a static model. These data are both *original data input* as listed in Table 4.1 (i.e. *segy* data, physical parameters measured at well or from laboratory test) and data input produced by other elements of the workflow listed in Table 4.2. An example is history matching, where the static model is improved in accordance to the results of dynamic data through an iterative process.

Table 4-1 Input data.

Data	**Source**	**Usage**
Previous seismostratigraphic and structural interpretation	Interpreted seismic data	Construction of 3D geological model
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 geolgical formations
Porosity	Measurements on core samples taken at wells or derived from logs	Define the porosity distribution within the geolgical formations
Permeability	Measurements on core samples taken at wells or derived from porosity and/or logs	Define the permeability distribution within the geolgical 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 at analogs when 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 paths 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 (already described?)	Baseline obtained from high resolution acoustic data	Construction of 3D geological overburden model

4.3.3 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. See Table 4.1 for a list of input data for the static model from other workflow elements.

Table 4-2 Input data 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

4.3.4 Results

The static model, constructed on the basis of the data mentioned above, should represent the storage complex conditions as realistically as possible. 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, as summarized as in Table 4-3.

Table 4-3 Results from static modelling, that are used in other workflow elements.

Result	**Description**	**Usage**
Interpreted key horizons	Map the layering of the storage complex	Used in ‘Dynamic modelling’

3D geological model	3D structure of the storage complex	Used in 'Dynamic, geomechanical modelling
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
3D fault and fracture framework	Built a fault model and identify compartments within the reservoir	Used in Dynamic, geomechanical modelling
Potential leakage points – Spill points from top reservoir surface	Identify possible leakage pathways	Used in Migration path analysis

4.3.5 Links with other workflow elements

The static model outcomes are inputs 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.

As already mentioned, 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.

4.3.6 Possible 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 risk factors are summarized below:

- Not enough or poor quality input data
- Low porosity that will lead to low capacity
- Low permeability
- Container integrity, where the seal 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.

4.4 Dynamic modelling

4.4.1 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 constrainted by threshold values of the maximum allowable reservoir pressure, arrival at 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 on the long term including the fate and migration of CO_2 in the storage compartment. In principle, the models used in Step 2 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 function of time and location.
5. Displacement of formation fluids such as brine in 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, COORESTM etc (section 8.3) 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..

4.4.2 Input

he following table describes the required input for a reservoir simulation.

Input	**Source**	**Usage**
Composition of the CO_2 injection stream	Operator	Input for the reservoir model
Planned injection rates	Operator	Input for the reservoir model
Configuration and location of wells	Operator	Input for the reservoir model
Hydrocarbon production data, initial hydrocarbons in place	Operator	History matching
Correct description of the PVT behaviour of CO_2 or mixtures containing CO_2 in particular near critical point:	NIST data (internet) or other published data sets	Input for the reservoir model

• Density • Viscosity		
Accurate initial pressure, temperature and composition of reservoir	Operator	Input for the reservoir model
Compressibility and viscosity of matrix and in-situ fluids	Operator	Input for simulation

4.4.3 Input from other workflow elements

The dynamic modeling also requires input from other elements within the overall feasibility workflow, as described in the following table.

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 – CO2 interaction	Geochemical modelling	Risk analysis, Renewed Capacity estimation

4.4.4 Results

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

Output data	**Use**
Pore pressure and temperature as function of time and location	Geomechanical modelling
Fate and migration of CO2	Geochemistry
Location of injection wells, injection rate for each well	Surface engineering
Storage capacity	Surface engineering
Near well temperatures	Surface engineering

4.4.5 Links with other workflow elements

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

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

- Static modelling. In 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 to be 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 pressure 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.
- Geochemical modelling. The pressure and temperature fields are input for the geochemical modelling of interaction between fluids (including CO_2) and matrix Field development plan. The choice of injection wells is one of the inputs for the field 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 ones are to be converted to injectors and which ones to monitoring wells. In case of new installations and wells (for example, for a virgin saline formation that is developed for CO_2storage), the injection strategy determines where injection site or sites must be constructed.
- Socio-geographic analysis. Like the previous item, the choice of injector wells can be affected by current land use, the proximity to (densely) populated areas and vice versa for sparsely populated areas.

4.4.6 Possible 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 (section 4.10). These results can include one or more of the following aspects.

- Requirements of additional heating of the CO_2. Heating is expensive and will affect the storage costs.
- Injection rates may be lower than the supply rate. This could result in additional storage sites to be required.
- Storage capacity could be different to that anticipated, e.g., from a high-level screening study. Again, this can lead to higher storage costs.
- CO_2 migration simulations show CO_2 will travel to an area too shallow/near fault/sea bed
- Very low porosity and permeability (tight) reservoir conditions
- Critical situation of the storage system (p & T conditions pre-injection)
- Pressure build up due to compartmentalisation of the reservoir or boundaries closed to fluid flow
- Adverse impact on receptor environments such as potable groundwater aquifer rocks, seabed or land surfaces
- Predicted simulations do not match the observed results

4.5 Geochemical analysis and modeling

4.5.1 Description of tasks

Geochemical reactions such as dissolution and precipitation are key trapping mechanism and are essential to understand long term storage activities. Once dissolved in brines, CO_2 may 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 aquifers.

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 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 modeling 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 striving at 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 modeling and the fluid flow modeling.

In addition other processes might be considered, such as:

- Microbial reactivity that could influence carbonate precipitation. Subsurface microbiological processes may affect- through biomineralization processes- CO_2 injection, stability of primary minerals as well as the precipitation of secondary mineral phases. Adapting some geochemical model could enable this kind of microbial process to be considered and the rate of carbonates bio-precipitation to be quantified. It may happen that biochemical processes accelerate the mineral carbonation, which is known to be the most stable and safe 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 isotopic composition for $\delta^{13}C$. 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 and not only at the sampling scale, with a 1D model diffusion, a long-term after injection phase. 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.

- CO2 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 CO_2.

4.5.2 Input

Input data for each site include 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 refer 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 groundwater flow that will control the equilibrium state. Information about the directions and rate of groundwater flow is also required to select samples in areas that could be affected by the CO_2 brine.

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 4.7. The rock matrix should also be characterized regarding the concentration of primary and secondary minerals in order to assess the solubility on the groundwater 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 groundwater and clay minerals is expected to control groundwater 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.

Table 4-3 Input data.

Data	**Source**	**Accessibility**
pH / alkalinity	Field measurement on water samples	Essential requirement / can be recalculated via modelling if not available
T, p		Essential requirement
dissolved oxygen, organic matter (for HC), any dissolved species		Commonly used
dissolved CO_2 (or P_{CO2})		Commonly used
Salinity		Absolutely required / possibly from literature
Na, K, Ca, Mg, Al, Fe, Mn, SiO_2, SO_4, Cl, S, PO_4	Laboratory measurements on water samples	Main elements and essential requirement
mineral identification of rocks or well cements	Laboratory measurements on rock samples. Cation Exchange Capacity measured either on total rocks or	Essential requirement
mineral abundances		Essential requirement
CEC		Required

Mn and Fe extractable oxides	on clays	Required for an estimation of Redox
Surface area, porosity	Lab analyses	Required to estimate water/rock ratios and the available reactive surface areas

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

Specific input data (Table 4.4) are required for depleted reservoirs, in order to characterise the initial system, before injection has 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 if the modelling is in good accordance with the fields observations.

Table 4-4 *Elements and type of analyses that must be done to characterise the initial system (depleted reservoir) and the impact of the others 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. If the opportunity is possible, the results of these analyses ca, be extracted from literature.*

Samples from	**Analyses**	**Elements**	**Accessibility**
depleted reservoir	Major gases concentration	CO_2, C_1 to C_4, H_2S, N_2, H_2O	If available / From literature
	Noble gases concentration	He, Ne, Ar, Kr, Xe	
	□^{13}C	CO_2, C_1 to C4	
	Noble gases isotopes	^{3}He, ^{4}He, ^{36}Ar, ^{40}Ar	
injected CO_2	Major gases concentration	CO_2, O_2, N_2, H_2O	If available / From literature
	Noble gases concentration	He, Ne, Ar, Kr, Xe	
	Isotopic ^{13}C: □^{13}C	CO_2	
	Noble gases isotopes	^{3}He, ^{4}He, ^{36}Ar, ^{40}Ar	
capture process (in case of oxycombustion)	Major gases concentration	$O_{2,}$ impurities	If available / From literature
	Argon concentration	Ar	
	Noble gases isotopes	^{36}Ar, ^{40}Ar	

4.5.3 Input from other workflow elements

Input data as described above 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 filled with flow properties and also geochemical properties. See Table 4-5.

Table 4-5 *Input data 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	Impact of porosity and

	modelling	permeability on chemical reactions

4.5.4 Results

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

The outcomes of geochemical analysis are an update of mineral and fluid composition that affects the permeability and the porosity distributions.

Table 4-6 Results.

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

4.5.5 Links with other workflow elements

The pressure, at the end of injection, the displacement of gas phase versus liquid phase, and the 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 (log Q/K as chemical composition), pressure, temperature (in the most case fixed), evolution of pH and K/Phi for petrophysics variables.

- Geomechanical modelling: updated porosity and mineral composition to compute updated mechanical parameters / porosity update could be iterative,
- Dynamic modelling: geochemical analysis updated porosity and permeability. 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.

4.5.6 Possible risk factors

The main risk relies in the accessibility of data and samples. In addition, in case of very low permeability, it may be difficult (and expensive!) to determine properly 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 and thus 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.

4.6 Geomechanical analysis

4.6.1 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 front 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 case of an open aquifer, also through lateral migration. Therefore, it is essential to characterize the continuity and the thickness of the seal, 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 in the formation pressure, due both to the injection rate and the volume of CO_2 and buoyancy forces, 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 first precise fluid-flow modelling (with a good permeability and connected porosity evaluation), and also, to ensure a good mechanical analysis, the characterization of initial stresses, fault distribution and rock strengths. In saline formations, pressure management is essential to control deformation in the surrounding rock matrix. This overpressure may 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.

4.6.2 Input

Data for geomechanical baselines can be extracted from interpretation of logs and experiments on cores. If data are not available, literature will help in determining a range of values to be tested.

Table 4-7 Input data.

Data	Source	Accessibility
Initial geomechanical rock properties (E, ν)	Sonic log/ laboratory experiments	Essential requirement (from literature if not available)
initial stress	Leak-off test & density log / world stress map	Essential requirement (from literature if not available)
Failure criteria for seal and fault (friction angle, cohesion)	Laboratory experiments / phenomenological laws	Essential requirement (from literature if not available)
Thermal dilation coefficient	Laboratory experiments	If available
CO_2 impact on rock mechanical properties (E, ν, friction angle, cohesion)	Laboratory experiments	If available

4.6.3 Input from other workflow elements

Data presented above 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.

ΔP and ΔT data, coming from the dynamic modelling, are input of the geomechanical modeling. They represent variation in pore pressure and in temperature (relatively to a reference date).

Table 4-8 Input data from other workflow elements.

Input	**Source**	**Usage**
$\Delta P(x,y,z,t)$, $\Delta T(x,y,z,t)$	Dynamic modelling	Loading of the geomechanical modeling
(regional) static model with 3D fault framework	Geological static modelling	Geomechanical model geometry
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

4.6.4 Results

Once the geomechanical modelling is performed, the natural outputs are strains and stresses through the entire model. For this study, it should be determined where failure criteria have been reached and for which injection pressure level.

Table 4-9 Results.

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

4.6.5 Links with other workflow elements

- Geological static modelling: a structural model up to the surface including faults filled with initial porosity is required at the beginning of the geo-mechanical modelling (non iterative). The consistency of geo mechanical data (Table 4.10) with litho 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 value of the injection pressure that induces damage to help in determining injection strategies.
- Migration Path analysis: results can be used to help in identifying possible weak area where the failure criteria have to be determined.

- Risk analysis: Geomechanical modelling gives a clue on the risk of geomechanical failure for a given injection scenario. It also gives the value of the injection pressure that induces damage.

4.6.6 Possible risk factors

One risk relies on the availability of relevant data to estimate geomechanical behaviour law integrating geochemical aspects.

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

4.7 Well integrity analysis

4.7.1 Description of tasks

Potential migration from the reservoir along wells is generally considered as the major hazard 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 (debonding) and lead to annular pathways along the interfaces between cement and casing or host rock

According to the EC Directive on storage (2009/31/EC and its guidelines) 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 safe long-term containment of the CO_2 underground, some criteria for well barriers (Figure 4.1) 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 caprock — and to the atmosphere. These typically include the cement section outside the production casing adjacent to the formation rocks and the production casing itself. Thereby special attention has to be paid to the existence and performance of the cement (abandonment plugs and cement sheath) at the caprock 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, pressure tests) and during the productive life of the well (e.g. annular pressure information). A proper well integrity analysis is therefore highly dependant 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.

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

As demanded in the EU directive 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.

In order to be fit-for-CO_2 storage, some barriers of existing wells may need to be upgraded, based on the assessment, as 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.

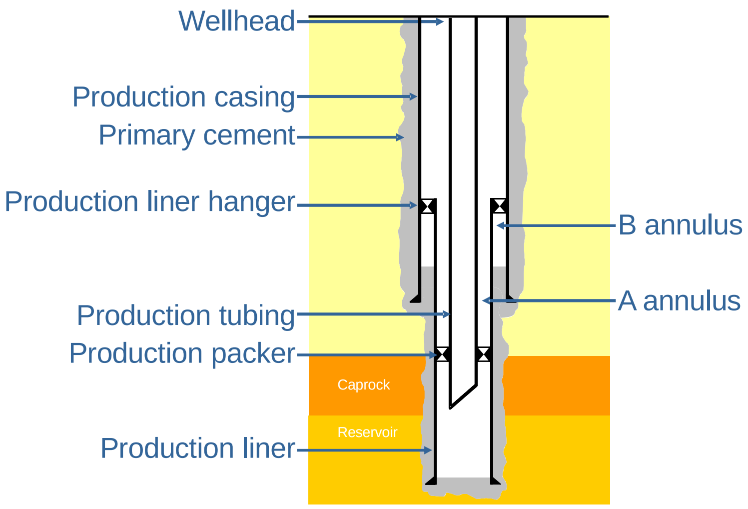

Figure 4.1 Well barriers in a generic well configuration

If there is no data to guide the analysis of the condition of the barrier, it should be stated clearly what the data gaps are and how uncertainties can be reduced in the analysis.

A proper evaluation of the performance of the well barriers will be essential for the subsequent steps risk assessment of the wells and the selection of potential corrective measures.

4.7.2 Input

All data needed for proper risk analysis:

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 4-10 lists the information, which is essential for the evaluation of the integrity of the wells in the storage area.

Table 4-10 Input data for risk analysis

Data	**Source**	**Usage**
Well tops	Interpreted well logs, Composite well logs (CWL)	Locate caprock 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 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

4.7.3 Input from other workflow elements

Essential input is required from the dynamic modelling task as well as from the geochemical and geomechanical simulations. 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 caprock and enter the reservoir.

Table 4-11 Input data from other workflow elements.

Input	**Source**	**Usage**
Lithostratigraphy	Static model	Define seal interval and intersection of well and caprock bottom
Intersection of well and bottom of the caprock	Static model	Locate precisely potential migration pathways
Pressure limits	Geomechanical analysis	Limits to bottom-hole pressure
Pressure at intersection caprock - wells (t)	Geomechanical analysis, Dynamic modelling	Mechanical stress load for well system
Temperature at intersection caprock -wells (t)	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

4.7.4 Results

The outcomes of this task will describe potential weak points of each of the existing wells in the storage area and will point out which leakage risks are generated by the wells in place. The potential risk, together with the accessibility of the wells, is therefore crucial for any risk analysis issues, for economical considerations and for establishing a proper remediation plan. Furthermore, the results of this workflow will be adopted in the migration path analysis.

Table 4-12 Results.

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
		Economical aspects

4.7.5 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 can be established which wells are connected with the CO_2 plume.

4.7.6 Possible risk factors

Well integrity issues present major hazards in the context of underground storage of CO_2. If 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, this presents 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 a case of an abandoned well these, counter measures can be (technically and economically) difficult and then may become a showstopper. For accessible wells the conduction of remediation works is generally technically feasible, but can be related to high costs.

4.8 Migration path analysis

4.8.1 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 old faults
- hydraulic fracturing and leakage due pressure build-up
- leakage through abandoned well(s)
- Intra reservoir baffles and variations in permeability
- Reservoir hydrogeology

The different factors that are controlling possible leakage are uncertain. It is therefore important to quantify the uncertainties in the input parameters and to model how these uncertainties may influence migration paths and leakage rates.

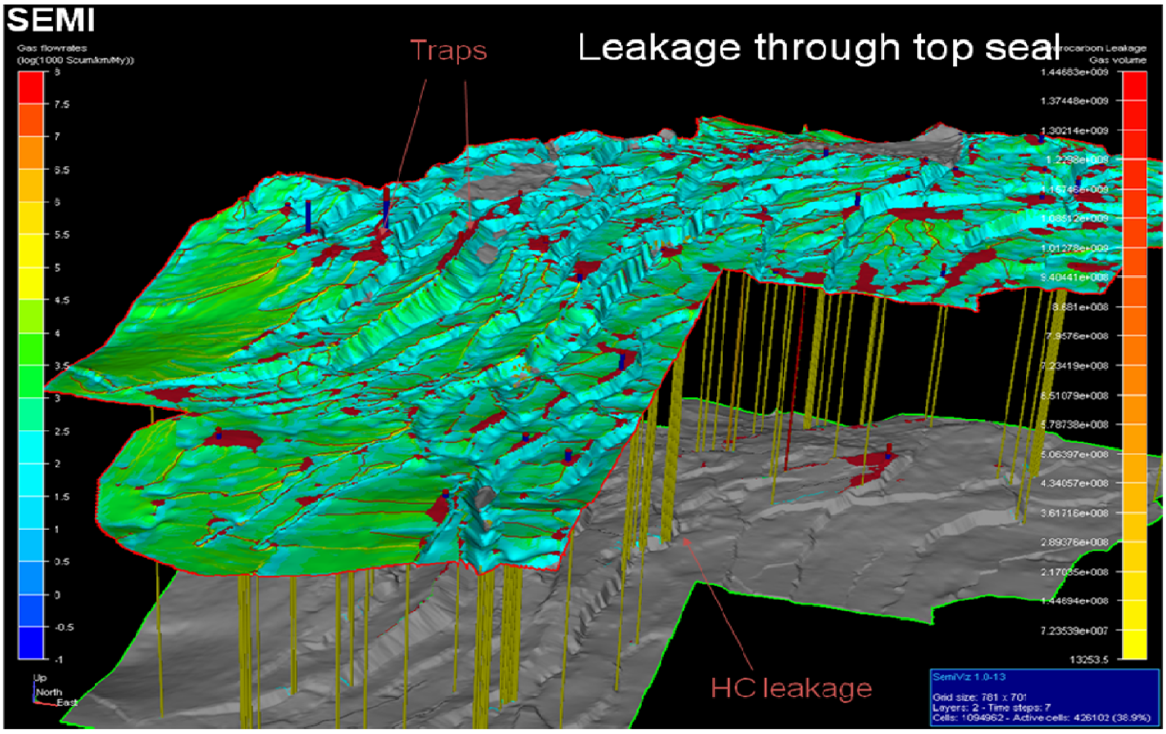

Figure 4.2 Example of how leakage from one reservoir to another through cap rock and faults can be simulated using a basin modelling tool (SEMI).

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. Then migration paths in the reservoir will be simulated, including capillary leakage through the caprock (Figure 4.2) and fault leakage. Possible software tools could be SEMI, PetroMod, COORES^{TM},. At least in SEMI, uncertainty can be addressed by varying the input parameter and use a Monte-Carlo sensitivity approach Figure 4.3). One weakness is that well integrity is not included and should be input from well integrity studies.

Another approach would be to use simulation results from static and dynamic modelling as input to the migration path analysis. This approach could utilise plume migration modelling from dynamic modelling software like e.g. Eclipse (see also software comparisons and references in, and spill point analysis for the top reservoir surface obtained from static modelling. Weak potential leakage points from wells should also be addressed. Fault properties could be input from geomechanical modelling.

The challenge is to integrate simulated results and knowledge from the different disciplines, to make a realistic sensitivity analysis on the possible risk for leakage. The complexity of the modelling will also be dependent on the geological storage complex. It will be easier to do proper leakage risk assessment in open aquifers, rather than in multilayer closed reservoirs. One possible further development will be software that take all the different leakage risks properly into account and that can do multiple simulations to estimate the uncertainty effectively.

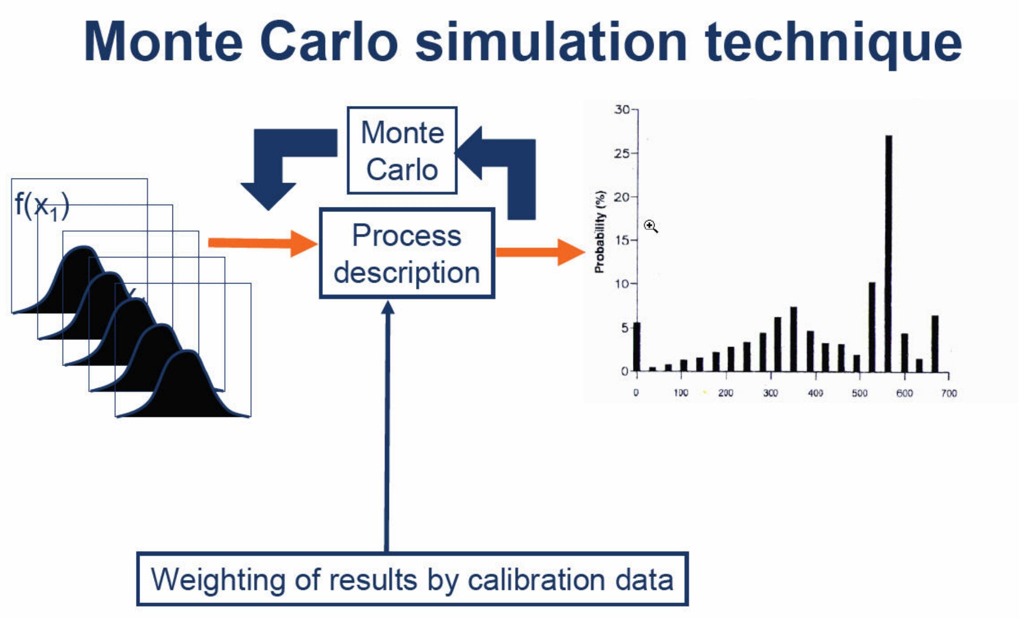

Figure 4.3 *Since all the input parameters hold large uncertainties, they should be varied and the probability of the result should be weighted.*

4.8.2 Input

Migration path analysis requires detailed knowledge about the geological setting; i.e. interpreted seismic horizons from reservoir and caprock, temperature, interpreted faults (throw, age and possible active periods should also be included), well logs with lithological units interpreted. This data would naturally come from a static model, but if they do not exist, they should be made solely for the migration path analysis.

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

Table 4-13 Input data.

Data	Source	Usage
Top and base map of reservoir unit (s)	Interpreted seismic horizons	Build 3D basin model
Interpreted units of the cap rock	Interpreted seismic horizons	Build 3D basin model
Reservoir properties	From well data and literature	Build 3D basin 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	Maps	To check if migration paths will conflict with other interests
Existing hydrocarbon fields	Maps	To check if migration paths will conflict with other interests
Surface infrastructure	Maps	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	Possibilities for reactivation of faults

4.8.3 Input from other workflow elements

The main input from other workflows are a 3D model of the basin reservoir and seal model with interpreted faults included, and 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 modelling or from basin modelling.

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, the casing may be most likely very thin and corrosion will rapidly cause a hole so that leakage will easily take place. Such analysis should be carried out in the well integrity study and should be used as input into the migration path analysis.

Table 4-14 Input data 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)

4.8.4 Results

Output of this part of the workflow will be a migration and leakage model that can estimate the areal and vertical extent of injected CO_2, migration path ways, flux rate of the migration, most likely leakage paths (e.g. old wells or old faults). Also the probability of leakage from the storage site should be aimed to be quantified.

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

Table 4-15 Results.

Result	Description	Usage
Properties for leakage points		Frac system characterization and human-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 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

4.8.5 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 path ways in wells, and input from dynamic modelling on position of injected CO_2 over time. The migration path analysis would be stronger if quantitative risks assessment could be included.

4.8.6 Possible risk factors

A key question to which migration path analysis aims to answer is to what extent the injected CO_2 migrates away from the injection sites(s) both with regard to distance and timing. It is therefore important to evaluate whether the migration will interfere with other subsurface applications e.g. oil and gas fields exploration. In addition, if the assumed projected storage structure is close to country borders, it is also important to assess potential migration via these borders. Other fields of potential interference are surface installations and potable water bearing aquifers affected by migration and 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.

When industrial large-scale storage of CO_2 will be more common and large amounts of CO_2 shall be stored, the pressure changes in underground should be considered as an important showstopper, if new seismicity and new fault movements are trigged. Geochemical analyses can also help the operator to justify without ambiguity whether there is a leakage or not.

4.9 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.

4.9.1 Description of tasks

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

- Unobtrusively measure relevant characteristics of the local population, describe local history, and describe other relevant local factors for each of the selected candidate storage locations;
- Increase public confidence in decision-making on the operation;
- Make available trustworthy generic and site-specific information on CCS.

4.9.2 Input

Table 4-16 Input data.

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

The EU Directive Aspects can be found in:

- Aarhus convention and related documents: http://ec.europa.eu/environment/aarhus/
- 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:

- Population density & other sociodemographics
- Area characteristics e.g. history, culture
- Pressing issues in area (e.g. other industrial projects)
- National context (e.g. regulatory)
- Relevant stakeholders
- Existing HC fields, Natura 2000 areas

4.9.3 Input from other workflow elements

Table 4-17 Input data from other workflow elements.

Input	**Source**	**Usage**
Technical site characteristics	All elements of the technical and economical characterisation (sections 4.1 through 4.15)	Public outreach

For the public outreach activities, input from technical site studies are required:

- Timing of decisions and activities

- Any available info about area e.g. relevant stakeholders, relevant issues
- Use of network to gain access to area, e.g. relevant parties/people involved in project
- Generic info on CCS in the country where the project takes place

4.9.4 Results

The results of the socio-geographic analysis can be input for the risk analysis (see section 4.9.6, below). These results are obtained from a qualitative and quantitative social site characterization: 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.

4.9.5 Links with other workflow elements

Progress or outcomes of technical site characterisation are to be shared with the general local public in the public outreach activities which are scheduled from 2012 onwards.

4.9.6 Possible risk factors

The main threat to social site characterisation is uncoordinated public outreach (when intention to CCS is made public by other parties). Identified risks related to technical site characterisation are:

- Restrictions to surface installations
- Environmental protected areas
- No political support
- No public acceptance
- Other use of subsurface, HC fields, gas storage, geothermal
- Local planner will not give permission
- Owner of store site does not agree to use or change of use
- Accessibility of the site

4.10 Quantitative aspects of site characterisation and risk assessment

To summarise, the steps in the site characterization process are the following:

- Site characterization
    - Quick Analysis
    - *Qualitative Risk Assessment*
    - Geological assessment
    - Geomechanical assessment
    - Geochemical assessment
    - Storage dynamic behaviour
    - *Full Risk Assessment*

"Site characterisation" will be undertaken in roughly the order described, but returning to an earlier issue might be necessary on account of later emergence of unanticipated risks. 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 for witnessing 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. Again it is wise to have regular contacts between the operator and the CA as to the expectations (CA) and obligations (Operator). In Chapter 2.2 the qualitative risk assessment was described. Here the focus will be on the quantitative and theoretical aspects, of the remaining workflow..

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 above. The salient 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 allowed 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 guessed 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 a lot of essential parameters are not all that well-known. It is important, then, to perform a sensitivity analysis to find out which parameters exactly most significantly affect the simulation results, therefore merit further characterisation to reduce their uncertainty. Intimately connected is the question of how many runs should be performed to cover 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. (Technical note: Here Buckingham's PI-theorem[2] comes in handy). From that information one can estimate the number of runs to be performed in order to reach adequate coverage of the parameter space.

- 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 global in nature (see above), nevertheless the calculations done on them should give trustworthy results. Actually, global 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. So, quite some communication is needed between adjacent steps, and hence between their executors. In the end each run is followed through the various steps until it reaches the biosphere where HSE questions are to be addressed. One must perform so many computations that for all parameters that are indispensable for this task one can establish a (joint) probability density function (pdf) for these parameters. All information about final uncertainty is contained in such a pdf. The question now is what we make of the results…

Criteria for acceptance of a site. 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." The intention is clearly that the storage be permanent. How the assessors have to determine this is not specified in the directive. We can assume that this is left to the national competent authorities to determine.

Obviously, the assessors will define issues that merit special care when drawing up field development plan. These will depend on the results of the quantitative RA.

4.10.1 Uncertainty

Let us address how to deal with *uncertainty* from a slightly more abstract perspective. It is slightly off the main road of this report, but is important nevertheless. It gives a unifying view on how we might consider uncertainty and deal with it in the numerical phases of the characterization. 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 & Then the risk is defined as

$$\text{Risk} \equiv \int p(\, q_1, q_2, \ldots |\, \text{Data}, I) \,.\, \text{Effect}\,(\, q_1, q_2, \ldots)\, dq_1\, dq_2 \ldots\ldots \qquad (1)$$

The integration extends over all of parameter space, with the understanding that Effect (q_1, q_2, …) may be zero for parts of the parameter space. In this formula p(q_1, q_2,…| Data, I) is the joint probability density function (pdf) of the parameter values q_1, q_2,… *consequential upon* the "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'

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[2] See, for example, http://www.math.ntnu.no/~hanche/notes/buckingham/buckingham-a4.pdf.

theorem) to the so-called *prior* probability that we attribute to Effect (q_1, q_2, …) before we have done all kinds of data processing / computational work. This is the initial situation to *guide* the workflow on the basis of perceived potential dangers. Put otherwise, this means somehow attributing a *prior quantitative judgment* to perceived dangers. Not something very shocking per se, but it is good to realize the consequences of the seemingly innocent definition in formula (1). Formula (1) represents a *generic* definition that pertains to the one animal called "Effect" here; there may be several separated risks.

How does this relate to the actions that we have undertaken once we followed the above track? In the qualitative RA phase, when we define different scenario's, these reflect the different "Effects" as mentioned in formula (1). So our qualitative phase determines which ones are to be investigated, and 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 modeling steps represents a point in (q_1, q_2, ….)-space. Suppose for sake of argument we only need the CO_2 flux per sq. 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 "flux m^{-2}" and "timespan of eruption". If we have covered our parameter spaces in the various steps in an honest way this pdf should be a fair representation of our *state of knowledge.* This state of knowledge includes our knowledge of the variability of all kinds of parameters in space and time as well.

It is good to mention that all we have done perfectly fit a Bayesian framework of probability and statistics. This is not so strange, given the fact that it can be proven that adherence to Bayesian rules is the mathematical consequence from adhering to some perfectly acceptable, even desirable rules of rationality. [see E.T.Jaynes (2003), Probability Theory, The logic of science, Cambridge; especially Chapter 2.]. We note in passing that this precludes using all kinds of fancy theories like "fuzzy logic", "possibility theory", which may well be consistent as theories, but are no good descriptors of uncertainty.

A last comment is in order. At the end of the site characterization the original assessment basis and risk identification and risk identification established should be re-iterated, because the site characterization may result in *new* findings on potential failure mechanisms (e.g. newly identified faults, imperfections in the seal etc.) Note, again, that by the qualitative risk assessment early in the process the steps of a technical geoscientific nature described earlier are acquiring more focus. Going through all steps requires continuous reflection upon what is easily explained, what is expected and what is potentially new and dangerous in a risk-sense. But the quantitative steps are to be taken roughly along the lines expounded.

4.11 Regulatory context

4.11.1 EC Legislation

The EC Directive on storage (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 Competent Authority, the liabilities associated with the site are transferred to the Competent Authority. 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 licence) 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.*

4.11.2 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 “**MVAR Protocol for CO_2 storage deep under the seabed of the North Sea**”.

Monitoring and Reporting Guidelines (MRG) for the inclusion of monitoring and reporting guidelines 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 a 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 (see also Chapter 5);
- 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 adding on 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 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[3] at injection;
- Breakthrough CO_2 from enhanced hydrocarbon recovery operations;
- Leakage from the storage complex.

4.11.3 An example of Member State regulations: The UK case

Schedule 2[4] (see 8.2) of the UK Storage of Carbon Dioxide (Licensing etc.) Regulations 2010 specifically outline the principle aims of monitoring in the UK which follow those prescribed in the Storage Directive (Section 8.1).

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[3] Fugitive emissions = Irregular or unintended emissions from sources which are not localised, or too diverse or too small to be monitored individually, such as emissions from otherwise intact seals, valves, intermediate compressor stations and intermediate storage facilities.

[4] http://www.legislation.gov.uk/uksi/2010/2221/contents/made

http://www.legislation.gov.uk/uksi/2010/2221/contents/made

4.12 Monitoring plans

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

- injected CO2 is behaving as expected,
- any migration or leakage occurs, and
- any identified leakage is damaging the environment or human health.

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

4.12.1 Developing a monitoring plan

Key stages in developing a monitoring plan are:

1. Select potential site, undertake preliminary site characterisation.
2. Identify risks
   a. Assessing risks might include (see section 4.10): leakage mechanisms (wells, caprock 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.
4. Design injection infrastructure and injection programme.
5. Reservoir modelling to predict site performance
6. Define monitoring domains (e.g. storage complex, wells, reservoir, overburden aquifer, surface) dependent on area of influence and risks– could be greater than storage complex
7. Identify key parameters to monitor to reduce risks
8. Identify appropriate monitoring tools. Selection criteria will include costs, reliability, access (especially offshore for wells/platforms), footprint of monitoring area, parameters to measure
9. Develop 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)
   d. Timing – continuous monitoring, frequency of periodic monitoring activities, when specific monitoring activities will start and finish
   e. How site performance (reservoir/plume behaviour, risk assessment, containment) will be revised in the light of monitoring data.
   f. Reporting
10. Conduct baselines for monitoring prior to injection – for Environmental Impact Assessment, reservoir performance
11. Monitoring during injection 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

12. Revise reservoir models and assess new risk profile
13. Revise monitoring plan if needed.
14. Following end of injection, 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 year. In the UK legislation leaves the actual period for post-inject monitoring to the discretion of the regulator on an individual case basis.

4.13 Site development plan

When the site characterisation study finds no obstacles to safe and 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 reservoir engineering) 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.

4.13.1 Timeline overview

Table 4.18 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 was estimated on the basis of an offshore platform, with 6 wells. The activities as well as the timeline will be quite different for a virgin aquifer, with no existing installations or wells.

Table 4.18 Timeline overview for converting a hydrocarbon field to storage site. Duration is indicative and based on a hypothetical offshore gas field.

	Task	**Duration**
1.	Feasibility study and high-level cost estimate (±40%)	6 months
2.	Concept selection	1 month
	Decision gate 1	–
3.	Environmental Impact Assessment (EIA)	1 year
4.	Option on reservoir	–
5.	Apply for funding	1 – 3 months
6.	Apply for licenses	1 year
7.	Pre-FEED[5]: design infrastructure, conceptual design	6 months
	Decision gate 2	–
8.	FEED: design infrastructure (detailed cost statement, ±15%)	1 year
	Decision gate 3	–
9.	Contract signing	–
10.	Engineering, procurement and construction (EPC)	6 – 9 months

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[5] FEED: front-end engineering and design: high-level design of installations. (Elements of) the installations are designed in detail and constructed in the EPC phase by subcontractors.

11.	Construction: well workover and abandonment	6 months
12.	Construction: platform modification	1 year
13.	Construction: pipeline	6 months
14.	Construction: onshore facilities (compression, pipeline)	6 – 9 months
15.	Tie-in work and commissioning	3 months
16.	Baseline monitoring	3 months
17.	Handover	–
18.	Start injection	–

4.14 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), the unit cost of storage (in terms of €/tCO_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 4.19. The geological properties of the reservoir and the required storage rate determine the timing of the transition from one phase to the next. The reservoir engineering activities (section 4.4) 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 net present value (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 Erreur ! **Style non défini..1**:

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

(**Erreur ! Style non défini.**.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 expression Erreur ! **Style non défini..2** for *f*:

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

(**Erreur ! Style non défini.**.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)*. As the costs in the different studies for RCI have been estimated on the basis of either a high-level screening (Phase 1) or a feasibility study (Phase 2), the values for the storage fee should be regarded as indicative, with an uncertainty of the order of at least 50%.

Table 4.19 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 costs

	mothballing	
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 online 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

4.15 Timeline

The relative order with respect to time of the building elements as described in this Chapter is given in (4.10). The well integrity analysis (4.7), and migration path analysis (4.8) are part of the dynamic behaviour phase. The socio-geographic analysis is obviously a part of the qualitative risk assessment. In the time table of section (4.13) the feasibility study is estimated as six months. However, the precise figure depends on the peculiarities of the site, man power involved and the time needed to obtain extra data after the screening phase. Also, one should not underestimate the time needed for communication between operator and CA. and the communication among the experts themselves. One might wish to take six months as something of a lower limit.

This linear ordering in the activities displayed in (4.10) is somewhat deceptive. In actual practice one might expect that quantitative work in geological, geomechanical, geochemical and storage dynamic assessments will put into question some of the assumptions on which they are built. Initial results may require reiteration of simulations with revised parameter values. Secondly, it is possible that in the qualitative phase something has been overlooked that shows up in the numerical work.

Consider for example a reservoir with extensive layer cake structures above. In the dynamic storage phase, one wants to see what happens with full-fledged leaking from the seal. It may turn out that the CO_2 hits a layer, cannot penetrate as long as the pressure is below a limit and starts to move sideways. This CO_2 might “pop up” at a location far from the site. Such an effect is easily overlooked in the qualitative phase, If not anticipated, such an effect would probably call for an iteration with time loss involved.

There is little point in trying to map out all possible “cross-overs”. These are highly site-specific and of a highly *ad hoc* nature. Site characterisation must yield certain results (see Chapter 5), but real research might also lead to real “surprises”.

5 EU Storage Directive

This section 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. This annex II consists of three steps, each of which consists of a list of items. These three steps are discussed below, 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 Document #2 provides an explanation of all the list elements; there is no need to repeat that here.

5.1 Data collection (step 1)

	Elements in step 1	**Workflow element(s)**	**Comments**
(a)	Geology and geophysics	4.1 and 4.2	Many data will come from the hydrocarbon industry (produced gasfields.) and must be gathered in phase 4.1 In the case of aquifers data might be scarce.
(b)	Hydrogeology (in particular existence of ground water intended for consumption)	4.5	
(c)	Reservoir engineering (including volumetric calculations of pore volume for CO_2 injection and ultimate storage capacity)	4.4	Data must come from hydrocarbon industry. In case of aquifers the paucity of data is a major problem.
(d)	Geochemistry (dissolution rates, mineralisation rates)	4.5	
(e)	Geomechanics (permeability, fracture pressure)	4.6	Lab experiments necessary.
(f)	Seismicity	3.0, and 4.1	Historic data
(g)	Presence and condition of natural and man-made pathways, including wells and boreholes which could provide leakage pathways	3.0	Data from hydrocarbon industry
(h)	Domains surrounding the storage complex that may be affected by the storage of CO_2 in the storage site	3.0	
(i)	Population distribution in the region overlying the storage site	4.9	
(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	3.0 and 4.1	

	1992 on the conservation of natural habitats and of wild fauna and flora(2) , potable groundwater and hydrocarbons)		
(k)	Activities around the storage complex and possible interactions with these activities (for example, exploration, production and storage of hydrocarbons, geothermal use of aquifers and use of underground water reserves)	3.0 and 4.1	
(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	3.0 and 4.1	

5.2 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	4.3	Any model starts with available data and geological background knowledge.
(b)	Geomechanical, geochemical and flow properties of the reservoir overburden (caprock, seals, porous and permeable horizons) and surrounding formations	4.4 and 4.6 and 4.7 and 4.8	The initial static model(s) is(are) a first best estimate. Loops are to be expected!
(c)	Fracture system characterisation and presence of any human-made pathways	4.3 and 4.6 and 4.8	
(d)	Areal and vertical extent of the storage complex	4.3 and 4.4 and 4.8	The migration pathway research validates or updates geological “suspicions” in 4.3
(e)	Pore space volume (including porosity distribution)	4.3 and 4.1 and 4.4	Migration path analysis will almost certainly yield modifications. To come from reservoir dynamic modelling
(f)	Baseline fluid distribution	4.3	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		1) Uncertainties in *model outline* can be tackled 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.		constructing several models. 2) Uncertainties in the parameters start a priori in the qualitative assessment. Here too the other phases do the updating!

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

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

5.3.1 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	4.4	
(b)	Efficacy of coupled process modelling (that is, the way various single effects in the simulator(s) interact)		Effectively all kinds of simplifications are made. Truly coupled modelling is seldom necessary…
(c)	Reactive processes (that is, the way reactions of the injected CO_2 with in situ minerals feedback in the model)	4.5	
(d)	Reservoir simulator used (multiple simulations may be required in order to validate certain findings)	4.4	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)	4.4 and 4.5	One may assume that once the container is filled and has come to rest geochemistry is a stand-alone part. For the injection phase a combination is necessary. Everything depends on the timescales to reach mechanical and thermodynamic equilibrium resp.

5.3.2 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	4.4	
(g)	Areal and vertical extent of CO_2 vs time	4.4 and 4.8	
(h)	Nature of CO_2 flow in the reservoir, including phase behaviour	4.4	The PVT charasteristics employed in the reservoir simulator should be above board.
(i)	CO_2 trapping mechanisms and rates (including spill points and lateral and vertical seals)	4.1 and 4.4 and 4.8	The static model already directs the research. Beware!
(j)	Secondary containment systems in the overall storage complex	Last point	
(k)	Storage capacity and pressure gradients in the storage site	4.4	
(l)	Risk of fracturing the storage formation(s) and caprock	4.5 and 4.6	Geochemical samples may give clues as to the minerals in the seal
(m)	Risk of CO_2 entry into the caprock	Last point	
(n)	Risk of leakage from the storage site (for example, through abandoned or inadequately sealed wells)	4.4 and 4.7	
(o)	Rate of migration (in open-ended reservoirs)	4.4	
(p)	Fracture sealing rates[6]	4.5, 4.6	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	4.5 and 4.4	See for the interplay between geochemistry and flow: Step 3.1e
(r)	Displacement of formation fluids	4.4	
(s)	Increased seismicity and elevation at surface level	4.6	

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[6] 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).

5.3.3 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 4.10 for how the Risk Assessment is to be performed.

5.3.4 Risk assessment: hazard characterisation (step 3.3.1)

This element of the SDEU 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 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	4.3 and 4.4 and 4.6 and 4.2	
(b)	potential magnitude of leakage events for identified leakage pathways (flux rates)		Follow the steps as described in 4.10
(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))	4.4	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	4.4 and 4.5	
(e)	any other factors which could pose a hazard to human health or the environment (for example physical structures associated with the project)	3.0 and 4.9	

5.3.5 Risk assessment: exposure assessment (step 3.3.2)

This element of the SDEU 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 CO2 from potential pathways identified under Step 3.3.1."*

The site characterization study will yield probability density functions for CO_2 fluxes, times… as deemed necessary by experts in HSE research and industrial safety. See 4.10 for details.

5.3.6 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 CO2 concentrations in the biosphere (including soils, marine sediments and benthic waters (asphyxiation; hypercapnia) and reduced pH in those environments as a consequence of leaking CO2). It shall also include an assessment of the effects of other substances that may be present in leaking CO2 streams (either impurities present in the injection stream or new substances formed through storage of CO2). These effects shall be considered at a range of temporal and spatial scales, and linked to a range of different magnitudes of leakage events.*”

5.3.7 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 characterization study will yield probability density functions for CO_2 fluxes, times, as deemed necessary by experts in HSE research and industrial safety. See 4.10 for details

6 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. The current document maps out a general route, but certainly does not describe a process that can be routinely followed. The reasons are summarized below.

The current version of the workflow is preliminary; the workflow will be tested in the five site characterisation studies included in the SiteChar project. Actual practice will possibly reveal bottlenecks hitherto unnoticed. At the end of the project, the workflow will be finalised and a further update of this document will ensue.

Here we summarise the general points in a characterization and assessment study.

1. The characterization 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. Next to the *formal* moments of contact between them, as indicated by the Storage Directive, it is necessary that the parties have a regular contact. These will inform the operator on what is expected from him in the study, and they should lead to a fuller understanding of the prospective site on the part of the CA. The interaction should speed up the process that will lead to exploration and storage permits when appropriate.
2. The process is *risk-based.* If the prospective site “survives” the screening phase points of attention and additional data requests will form a starting point for the characterization study. A qualitative risk assessment is the basis of further work. The expert team involved defines risks and associated adverse scenarios and the further work should always be based on their findings. Here again the informal contacts with the CA are a practical necessity. The further steps, numerical in nature, may show 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 characterization study should encompass a *quick scan, qualitative risk assessment, static modelling, dynamic modelling, geochemical analyses and modeling, geomechanical modelling, well integrity analysis, migration path analysis, socio-geographic analysis, quantitative risk analysis.* These phases have been described in this report. It must be stressed that the precise contents of the activities in each discipline should be determined in communication with the CA.
4. Further activities that follow from the characterization and assessment are drawing up a *monitoring 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,* just like the characterization and assessment proper.

The prime keyword in site characterization is “**risk-based**” and a second keyword is “**site-specific**”. In the characterization process one has to deal with risks that are essential in the concrete prospective site. This demand 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 Storage Directive, where terms like “significant risk of leakage” (Art. 4 sub 4) must be operationalized somehow by the national CA.

For the above reasons *regular communication* between operator and CA is a practical necessity. In order to speed up the process of site characterization and assessment such contacts are important as well.. Indeed, one should not lose sight of the fact that many sites have to be scrutinized within the coming decade in order to ensure a CCS offtake on a European scale.

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8 Appendices

8.1 ANNEX II of the EC Storage Directive

CRITERIA FOR ESTABLISHING AND UPDATING THE MONITORING PLAN REFERRED TO IN ARTICLE 13(2) AND FOR POST-CLOSURE MONITORING

1. Establishing and updating the monitoring plan

The monitoring plan referred to in Article 13(2) shall be established according to the risk assessment analysis carried out in Step 3 of Annex I, and updated with the purpose of meeting the monitoring requirements laid out in Article 13(1) according to the following criteria:

1.1. Establishing the plan

The monitoring plan shall provide details of the monitoring to be deployed at the main stages of the project, including baseline, operational and post-closure monitoring. The following shall be specified for each phase:

(a) parameters monitored;

(b) monitoring technology employed and justification for technology choice;

(c) monitoring locations and spatial sampling rationale;

(d) frequency of application and temporal sampling rationale.

The parameters to be monitored are identified so as to fulfill the purposes of monitoring. However, the plan shall in any case include continuous or intermittent monitoring of the following items:

(e) fugitive emissions of CO2 at the injection facility;

(f) CO2 volumetric flow at injection wellheads;

(g) CO2 pressure and temperature at injection wellheads (to determine mass flow);

(h) chemical analysis of the injected material;

(i) reservoir temperature and pressure (to determine CO2 phase behaviour and state).

The choice of monitoring technology shall be based on best practice available at the time of design. The following options shall be considered and used as appropriate:

(j) technologies that can detect the presence, location and migration paths of CO2 in the subsurface and at surface;

(k) technologies that provide information about pressure-volume behaviour and areal/vertical distribution of CO2-plume to refine numerical 3-D simulation to the 3-D-geological models of the storage formation established pursuant to Article 4 and Annex I;

(l) technologies that can provide a wide areal spread in order to capture information on any previously undetected potential leakage pathways across the areal dimensions of the complete storage complex and beyond, in the event of significant irregularities or migration of CO2 out of the storage complex.

1.2. Updating the plan

The data collected from the monitoring shall be collated and interpreted. The observed results shall be compared with the behaviour predicted in dynamic simulation of the 3-D-pressure-volume and saturation behaviour undertaken in the context of the security characterisation pursuant to Article 4 and Annex I Step 3.

Where there is a significant deviation between the observed and the predicted behaviour, the 3-D model shall be recalibrated to reflect the observed behaviour. The recalibration shall be based on the data observations from the monitoring plan, and where necessary to provide confidence in the recalibration assumptions, additional data shall be obtained.

Steps 2 and 3 of Annex I shall be repeated using the recalibrated 3-D model(s) so as to generate new hazard scenarios and flux rates and to revise and update the risk assessment.

Where new CO2 sources, pathways and flux rates or observed significant deviations from previous assessments are identified as a result of history matching and model recalibration, the monitoring plan shall be updated accordingly.

2. Post-closure monitoring

Post-closure monitoring shall be based on the information collected and modelled during the implementation of the monitoring plan referred to in Article 13(2) and above in point 1.2 of this Annex. It shall serve in particular to provide information required for the determination of Article 18(1).

8.2 Schedule 2 of the UK Storage of Carbon Dioxide (Licensing etc.) Regulations 2010

2.—

(1) The operator must carry out a programme of monitoring of the storage complex and injection facilities, for the purposes specified in sub-paragraph (3).

(2) Such monitoring must include (where possible) the monitoring of the CO_2 plume, and (where appropriate) of the surrounding environment.

(3) The purposes are—

(a) the comparison of the actual and modelled behaviour of the CO_2 (and the naturally-occurring formation water) in the storage site;

(b) the detection of any significant irregularities;

(c) the detection of any migration of CO_2;

(d) the detection of any leakage of CO_2;

(e) the detection of any significant adverse effects on the surrounding environment, and in particular on—

(i) drinking water,

(ii) human populations, and

(iii) users of the surrounding biosphere;

(f) the assessment of the effectiveness of any corrective measures taken;

(g) updating the assessment of the safety and integrity, both short- and long-term, of the storage complex (including the assessment of whether the stored CO_2 will be completely and permanently contained).

(4) The monitoring must be based on the monitoring plan.

(5) The monitoring plan must be updated in accordance with Annex II to the Directive, and in any event within five years of the approval of the original plan, in order to take account of—

(a) changes to the assessed risk of leakage;

(b) changes to the assessed risks to the environment and human health;

(c) new scientific knowledge; and

(d) improvements in best available technology.

(6) The updated plan must be submitted for approval by the authority.

(7) The authority may—

(a) approve that plan, or

(b) require the operator to make such modifications to it as the authority (after consulting the operator) considers necessary, and the updated monitoring plan is the plan as so approved or modified.

(8) Sub-paragraphs (5) to (7) apply to the further updating of an updated plan as they apply to the updating of the original plan.

8.3 Software Glossary

Abaqus (Dassault Systèmes) *http://www.simulia.com/download/pdf/Abaqus%20Unified%20FEA%20Brochure.pdf*
Coores™ (IFPEN) Coores™ (CO_2 Reservoir Environmental Simulator) is a research code designed by IFPEN to study CO_2 storage processes from the well to the basin scale ([1, 2, 3, 4, 5, 6]). Coores™ is specified, developed and validated through a collaboration between several departments: Applied Mathematics, Reservoir Engineering, Geochemistry and Thermodynamics Departments. The geometry model allows users to map medium properties with a high precision by using a high flexibility in the cell size, shape and pattern and therefore to minimize the number of cells required to achieve a good porous medium description. With a structured or unstructured grid, Coores™ simulates multi-component three-phase and 3-D fluid flow in heterogeneous porous media. Molar conservation equations are solved with a fully-coupled system linearised by a Newton approach. To take into account mineralogy changes, the transport model is coupled with a geochemistry reactor, Arxim (Ecole des Mines de Saint-Etienne

– IFPEN collaboration). Permeability and capillarity pressure changes due to porosity variations are take into account with different porosity-permeability and porosity-capillarity pressure laws such as Kozeny-Carman, Labrid or Fair-Hatch laws [7].

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Eclipse (Schlumberger)

http://www.slb.com/content/services/software/reseng/index.asp?

gOcad® (Paradigm)

http://www.pdgm.com/products/gocad.aspx

OpenGeoSys (head developer: UFZ Leipzig, Germany)

OpenGeoSys (OGS) is a scientific open source project for the development of numerical methods for the simulation of thermo-hydro-mechanical-chemical (THMC) processes in porous and fractured media. OGS is implemented in C++, it is object-oriented with a focus on the numerical solution of coupled multi-field problems (multi-physics). Parallel versions of OGS are available relying on both MPI and OpenMP concepts. Application areas of OGS are currently CO_2 sequestration, geothermal energy, water resources management, hydrology, and waste deposition [1].

[1] *http://www.ufz.de/index.php?en=18345*

Petrel (Schlumberger)

http://www.slb.com/content/services/software/geo/petrel/index.asp

PRESSIM3D (SINTEF PR)

The PRESSIM software is a forward pressure simulator that calculates water fluid flow between pressure compartments defined by faults [1, 2] on basin scale (but also on reservoir scale). The main principle is to simulate pressure generation and dissipation over geological time scale and the resulting pressure distribution. Pressure simulations are also carried out on shorter time scale, calculating the 3D fluid flow both laterally in the reservoir units, and vertically in the shaly cap rock units using Darcy flow. Fracturing and leakage due to high overpressures are also simulated [3]. It is necessary to model the migration of the CO_2-phase due to buoyancy using relative permeability and at the same time have the models to identify and describe possible hydraulic leakage. It is thus possible to achieve a best calibrated case out of a large number of simulations that may form a basis for uncertainty and sensitivity analyses.

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SEMI (SINTEF PR)

SEMI is originally a secondary HC migration modelling tool developed for basin scale [1]. It uses a ray-tracing scheme and parallel computing techniques to model petroleum migration within stacked carrier rock sequences at high resolution. It also handles the processes that cause hydrocarbons to migrate out of traps and provides advanced methods for predicting and accounting for fault seal capacities in migration modelling. SEMI includes routines for the vertical decompaction of depth maps. Monte Carlo simulation methods are incorporated, making the program well suited for sensitivity studies and for assessing key risk factors. Standard input to SEMI includes depth map grids and fault trace files. In addition, SEMI can utilise palaeobathymetric data.

During the last years new developments have been started to make the tool suitable for CO_2 migration and storage modelling [2, 3]. The software handles not only an equation of state (i.e. partitioning of CO_2 into supercritical and aqueous phase) but also physicochemical processes. Main processes include viscous fingering, diffusion controlled migration along faults, and chemical interactions between dissolved/supercritical CO_2 and mineral phases/formation waters (i.e. precipitation and solution of minerals). We are currently further developing our in house software including efficient loss functions for these physicochemical processes.

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loss behaviour in CO_2 underground storage sites using process-based basin modelling software. Submitted to 10th International Conference on Greenhouse Gas Control Technologies, 19-23 September 2010, Amsterdam, 2010.
STARS (Computer Modelling Group, *www.cmgroup.com***)** STARS is a three-phase multi-component thermal reservoir simulator (with local grid refinement, three-phase relative permeabilities and capillary pressures, flexible boundary conditions) extended with a geomechanical model.
TOUGH2-FLAC-3D (LNBL, Itasca) TOUGH-FLAC is a simulator based on two existing well-established codes, each specialized to multi-phase flow, heat and reactive transport or heat transport and geomechanical processes, which were coupled to potentially cover all THMC processes. Both codes - TOUGH2 [1], a THC code, and FLAC-3D [2], a THM code - are linked using sequential execution and data transfer through non-linear coupling functions. The TOUGH2 code solves coupled problems of non-isothermal, multi-phase, multi-component fluid flow in complex geological systems. It has been verified and used by many groups all over the world to study problems in geothermal energy, oil and gas reservoirs, contaminant migration and nuclear waste isolation. The FLAC-3D code is developed for rock and soil mechanics and can also handle coupled thermo-mechanical and hydromechanical processes for single-phase fluid flow. Although, in principle, a sequential coupling of two codes is less efficient than having a single code, a big advantage with coupling of TOUGH2 and FLAC-3D is that both codes are well tested and widely applied in their respective fields [3]. [1] Pruess K. TOUGH2—a general purpose numerical simulator for multiphase fluidandheat flow. Lawrence Berkeley National Laboratory Report LBL-29400, 1991. [2] Itasca Consulting Group Inc. FLAC-3D Manual: Fast Lagrangian analysis of continua in 3 dimensions–Version 2.0. Itasca Consulting Group Inc., Minnesota, USA, 1997. [3] Rutqvist, J., Wu, Y.-S., Tsang, C.-F., Bodvarsson, G.A., Modeling approach for analysis of coupled multiphase fluid flow, heat transfer, and deformation in fractured porous rock. Int. J. Rock Mech. Min. Sci. 39, 429-442, 2002.
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