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Energy Procedia 00 (2013) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

GHGT-11

The SiteChar approach to efficient and focused CO_2 storage site characterisation

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Abstract

Carbon Capture and Storage (CCS) is one of the solutions that can significantly reduce CO_2 during the transition from fossil fuel-based energy to an energy system based on renewable energy sources. Recent studies point out that sufficient storage capacity in saline aquifers and depleted gas fields is available to permanently store several decades worth of current CO_2 emissions. Nevertheless, a significant hurdle for the post-demonstration phase of CCS development is the lack of proven and tested storage reservoirs. One of the goals of the EU FP7 SiteChar project is to develop an efficient site characterisation workflow, to support the development of the numerous storage sites that will be needed for large-scale deployment of CCS. The workflow is designed to address all aspects of safe and secure storage required by the EU Storage Directive. The links between the Storage Directive requirements and the site characterisation workflow are described in detail. The workflow is currently being applied to five sites suitable for CCS across Europe. A final version of the workflow will be published early 2014.

Selection and/or peer-review under responsibility of GHGT

Keywords: CCS; CO_2 storage, site characterisation, EU Storage Directive.

1. Introduction

Amongst all greenhouse gases CO_2, whose atmospheric concentration rose from pre-industrial levels of 280 ppm to 380 ppm measured in 2005 is the most important, being responsible for about two-thirds of the enhanced greenhouse effect [insert reference]. Although some discrepancies exist on the extent of the consequences, all climatic models predict a significant global warming in the decades to come. The large-scale implementation of Carbon Capture and Storage (CCS) at power generation and large industrial plant will contribute to reduce CO_2 emissions and future adverse climatic effects. The storage capacity of deep geological formations is estimated to be sufficient to permanently store several decades-worth of CO_2 emissions into the future (e.g., for Europe: see [1]). Saline aquifers offer the largest global storage potential of all geological CO_2 storage options and are widely distributed throughout sedimentary basins, but are poorly characterised. Oil and gas fields are considered to be good potential storage sites as they are well characterised but have smaller total 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 [2, 3]. The development of a CO_2 storage site, which includes exploration, characterisation and infrastructure development, 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 and remains the highest risk component in the CCS chain. It is therefore essential to start characterising the storage sites as early as possible in the development of CCS projects. This paper presents the result of one of the central goals within the EU FP7 SiteChar project: to develop a workflow for site characterisation studies for the storage of CO_2. The workflow defines the different phases of the site characterization process needed to comply with the EU Storage Directive [4] and aims to result in efficient and complete characterisation.

Recent reports address the work to be undertaken in the characterisation of a CO_2 storage site [5-9]. A number of aspects of the site characterisation process are not or partly covered:

- The sequence of the different characterisation steps and the timing of the process;
- Interdependencies and feedback loops within the characterisation process;
- The coverage of the different aspects of the EU Storage Directive in the process.

A clear description of these aspects will streamline the site characterisation process, and make sure that the output covers all aspects required by the EU storage directive.

It is important to emphasize that site characterisation is a multidisciplinary effort (Figure 1). It is similar to oil and gas exploration; in the case of CCS the focus and area of study are different. While in hydrocarbon exploration the emphasis is on the reservoir, a CO_2 storage feasibility study must qualify the storage complex, which includes the reservoir, the cap rock, any secondary storage formations, secondary seal rocks and the overburden. However while in hydrocarbon exploration the object of study is a proven reservoir, for CO_2 storage the ability of a geological structure to trap and permanently retain CO_2 must be demonstrated. A site characterisation study should also answer the questions asked to satisfy the permit requirements as described in the EU Directive. This calls for estimating the risks associated with CO_2 storage in a given storage complex and assessing how these can be mitigated through site design and injection planning. When the risks fall below an a priori defined threshold, the site can be used for storage. Risk assessment is considered as the focus of the workflow, contributed by all areas of expertise involved in a site characterisation study. Related issues are public awareness measures and public information provision which are mentioned in the EU Directive as important aspects to consider. To address these concepts, another part of the SiteChar project is devoted to social site characterisation which is described in a separate paper [10].

The primary aim of the SiteChar site characterisation workflow is to clarify the links between the results from different areas of expertise (geology, geomechanical and reservoir engineering, etc.) and how the results combine to answer all issues listed in the EU Storage Directive. The workflow must be risk based and site specific; it is tested at the five potential storage sites, selected as representative of various geological contexts (extensive geological strata and structural traps, depleted hydrocarbon reservoirs and saline aquifers, located onshore and offshore) across Europe. The SiteChar workflow should be the basis for a uniform approach to site characterisation in Europe, a gap identified by the IEA [11].

Apart from the technical aspect of defining a workflow there is an 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 workflow is intended as a basis for discussions between the site operator and the CA. The EU Storage Directive suggests that a massive program of investigation should be conducted, but for a specific site certain parts of the program might be more relevant than others. The operator and CA must agree on which research is deemed sufficient in order to comply with the requirements of the Storage Directive. The interplay between operator and CA should have a continuous character, which will lead to a better understanding by the CA of the specific characteristics of the proposed site and of the essential activities and results for a permit application [12]. It will also lead to a clearer focus for the operator on the deliverables at the formal points in the process.

Thus, the SiteChar workflow will lead to focused and efficient site characterisation studies and will help develop the certified storage capacity that is required for large-scale CCS.

2. Method

A site characterisation study generally commences with screening and selection of the potential sites, consisting of an investigation of the options for storage in a given area or region. The workflow presented here combines the (high-level) screening study with a (detailed) site characterisation study. The workflow is graphically presented in Figure 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. 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 site to trap and permanently retain CO_2 must be demonstrated. In fact, given the geological uncertainties, the aim of a site characterisation study is to reduce the risks that are associated with CO_2 storage in a given storage complex and determine the extent to which these can be mitigated. If the risks are acceptable to the CA and the storage project operator, the site can be used for storage. The areas of expertise that must be covered by the team include:

- structural geology / sedimentology / petrophysical analysis;
- reservoir engineering;
- geomechanical modelling;
- geochemical analysis and geochemical modelling;
- well engineering;
- risk assessment;
- economical analysis;
- engineering and design of injection facilities;
- social research.

Social research is also performed within the SiteChar project and presented in a separate paper [10].

The workflow can be separated into two main elements: screening study and characterisation study.

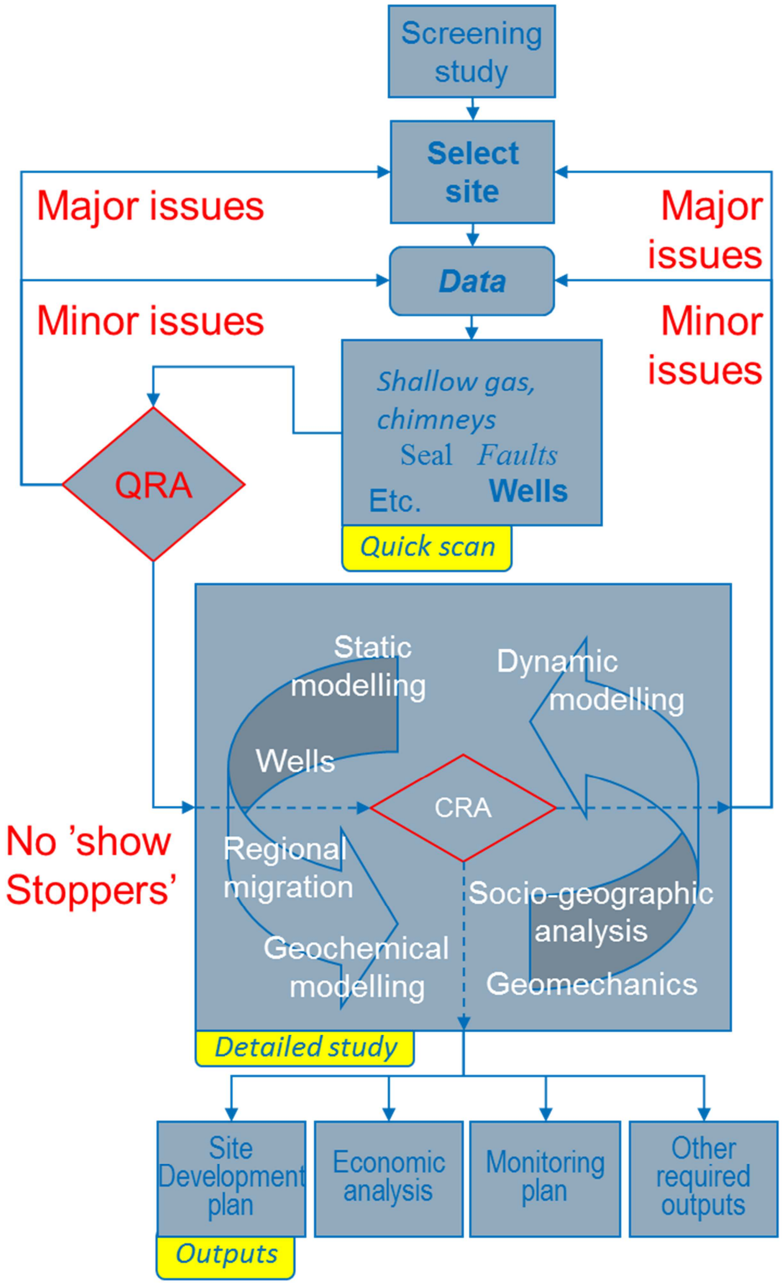

Figure 1. Workflow of the characterisation and assessment. The first step after selection of a site is a quick scan of available data and a Qualitative Risk Analysis ("QRA"). Issues found at this time could lead to the collection of more data ("minor" indicating minor issues), or, when major issues are found, to discarding the site and selecting a new site. When no issues are identified ("no show stoppers"), a detailed site characterisation is started, represented by the large box. The activities in the characterisation revolve around a Continuous Risk Assessment ("CRA"), with extensive exchange of data and results between the different areas of study. When no hurdles to safe and secure storage are found, the results from the site characterisation are the basis for, inter alia, the site development plan, cost analysis and a monitoring plan.

2.1. 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 and timing of supply) and economic considerations (distance from the capture plant, cost of storage, other uses of the pore space). Risk assessment starts 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 conditions. 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 (see, e.g. [13]). The expected output of the screening phase is a list of promising potential storage sites. Further selection, to arrive at the site to be studied in detail, will be on such grounds as economic (expected cost) and / or technical (expected complexity of the site).

2.2. SITE CHARACTERISATION STUDY.

The next detailed phase of investigation is that of ”site characterisation” which is intended to either elevate such sites to the status of “suitable” or dismiss them as ‘unsuitable’. It comprises a number of steps described in the following paragraphs.

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 for reservoir characterisation if the field owner is undertaking the storage site assessment. Well data, production data and reservoir models may be available. However, data for the characterisation of the overburden might not be sufficient. 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 the case of a virgin formation, with few or even no wells penetrating the formation, this first step might involve active data collection: shooting a seismic survey, collecting 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 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 may be less interested in the mechanical properties of the seal, whereas this aspect is of paramount importance for the final assessment of the site’s suitability for CO_2 containment. Hence, the CA should view the data with respect to 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 covering the areas listed above consider all the available data. A qualitative risk assessment has to be undertaken as soon as possible during the characterisation phase. The quick analysis is followed by a workshop with the specialists from the team, who define the risks associated with the site. These risks are related to the safety and security of storage, as well as the conformity 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.

c. When the initial qualitative risk assessment is completed, the site is studied and modelled by the different areas of expertise. This is represented by the large rectangular box in Figure 1, which highlights a number of issues from the respective expert areas. This is the most time-consuming and also the most complex part of the study, requiring intensive interaction within the team. Special attention should to be paid to the exchange of data and sharing of results among the experts and how their results apply to elements of the storage directive. The arrows in the box represent the iterative nature of the work, with data and results being exchanged continuously among the different areas of expertise.

d. Once all aspects of safe and secure storage have been studied and internal consistency in results and data is reached, some risks can be assessed more quantitatively. Risks are compared to a priori determined risk threshold(s). Adequate mitigation measures are then defined 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 shortlisted by the screening study.

e. If the risks fall below established threshold(s), e.g. because there is the option of mitigation through site design, choice of injection strategy or monitoring, the last elements of a site characterisation study discussed here can start. These elements include setting up a monitoring plan and baseline studies, drafting a site development plan, setting up a plan for the mitigation and remediation of leakage (a corrective measures plan) and analysing the costs of storage. The monitoring and corrective measures plans are 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.

3. Risk-based, site-specific action and research questions

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 more probable or high consequence scenarios that may lead to significant irregularities have to be investigated in detail. Obviously then, the qualitative phase for risk assessment is 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.

It should be clear which particular issues must be addressed for a particular site by the investigators. These questions will lead the subsequent investigations; they guide the activities. The nature of these questions is such that without proper answers no storage permits can be issued and are therefore considered the priority issues.

During the following phases, when quantitative detailed analyses are undertaken, it is quite possible that new risks are discovered. In fact, any quantitative investigation is not only directed at getting numerical values, but also at getting a fuller picture of what happens and which processes are likely to have greatest affect on storage site performance. If and when such new risks are identified, the characterisation process has to be reiterated. The questions posed at the beginning are either augmented or changed.

From a practical stance it might be appropriate to formalize the process and appoint persons whose task is to make sure that new risks are included as appropriate. The CA and the operator should decide what has to be done, so as to smooth the process, and avoid delays at the formal moments in the storage process. The risk assessment process is likely to be iterative as the site characterisation progresses and more information becomes available.

4. Basic considerations on risk assessment

Before a proper risk assessment can take place, the assessment basis must be defined, i.e. type(s) of risks actually assessed must be identified 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 human Health, Safety and the Environment (HSE). [Note that in all kinds of "official" documents risk assessment in connection with CO_2 storage is always interpreted on the basis of HSE. However, for a site operator, economic, legal and reputational risks are important and they would undertake a risk assessment on this basis as well as on HSE issues. This aspect is usually treated somewhat differently by financial-economic specialists.]

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, as mentioned above. Such a mode of behaviour is prudent: in this way the whole process will be better focused. The main risks that can be identified 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 aseismic 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 include all involved disciplines to properly identify and prioritize the risks and technical issues. 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.

5. Conclusions

This paper describes the workflow for a site characterisation study, as required to satisfy the permit requirements defined in the EU storage directive. The current version of the workflow is preliminary; the workflow is tested in the five site characterisation studies included in the SiteChar project, to reveal any unanticipated bottlenecks. In two of these sites, a dry-run licence application procedure is followed in the project [12]. The final version of the workflow will include the relevant lessons learned from these test cases.

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

1. The characterisation study intends to fulfil the obligations laid down in the EU Storage Directive. Three parties are involved: the operator of the prospective site; the CA; the EC who will review the storage application. Next to the formal moments of contact between them, as indicated by the Storage Directive, it is necessary that all the parties have 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 characterisation study. A qualitative risk assessment is the basis of further work. The expert team defines risks and associated adverse scenarios and further work should always be based on their findings. Here again the informal contacts with the CA are a 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 analysis and modelling, geomechanical modelling, well integrity analysis, migration path analysis, socio-geographical analysis and quantitative risk analysis. These phases are described in the SiteChar report [14]. It must be stressed that the precise contents of the activities in each discipline should be determined in communication with the CA.
4. The site characterisation and assessment is followed by activities such as drawing up a monitoring plan and a site development plan. It is to be noted that the monitoring plan is also risk-based and site-specific, just like the characterisation and assessment proper.

Keywords in site characterisation are "risk-based" and "site-specific". In the characterisation process one has to deal with site-specific risks. This makes it difficult to specify all the actions to be undertaken by the investigators as if they are an obligatory list: 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 clearly defined by the operator and 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 characterisation 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 implementation of CCS on a European scale.

Acknowledgements

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under grant agreement n° 256705.

References

[1] Vangkilde-Pedersen T, Lyng Anthonsen K, Smith N, Kirk K, Neele F, van der Meer B, Le Gallo Y, Bossie- Codreanu D, Wojcicki A, Le Nindre Y-M, Hendriks C, Dalhoff F, Christensen NP. Assessing European capacity for geological storage of carbon dioxide–the EU GeoCapacity project, *Energy Procedia* 2009; **1**, pages 2663-2670.

[2] CO2Europipe. *Developing a European CO_2 transport infrastructure*, CO2Europipe report D1.1.1, 2011 (www.co2europipe.eu).

[3] Neele F, Mikunda T, Seebregts A, Santen S, van der Burgt A, Stiff S, Hustad C. A roadmap towards a European CO_2 transport infrastructure, *Energy Procedia*, 2013; this volume.

[4] EU. Storage Directive 2009/31/EC, 2009 (http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF).

[5] CO2CRC. *Storage capacity estimation, site selection and characterisation for CO_2 storage projects*, CO2CRC report RPT08-1001, 2008.

[6] DNV. *CO2Qualstore – Guideline for selection and qualification of sites and projects for geological storage of CO_2*, DNV report 2009-1425, 2009.

[7] NETL. *Site screening, selection and initial characterization for storage of CO_2 in deep geological formations*, DOE report DOE/NETL-401/090808, 2010.

[8] EU. *Implementation of Directive 2009/31/EC on the geological storage of carbon dioxide – Guidance document 2 – Characterisation of the storage complex, CO_2 stream composition, monitoring and corrective measures*, 2011 (ec.europa.eu/clima/policies/lowcarbon/docs/gd2_en.pdf).

[9] Neele F, Nepveu M, Hofstee C, Meindertsma W. *CO_2 storage capacity assessment methodology*, TNO report TNO-060-UT-2011-00810, 2011 (report available at http://www.globalccsinstitute.com/publications/CO2-storage-capacity-assessment-methodology; file accessed June 4, 2012)

[10] Brunsting S, Pol M, Mastop J, Kaiser M, Zimmer R, Shackley S, et al. Application of social site characterisation to inform public engagement in Poland and Scotland *Energy Procedia*, 2013; this volume.

[11] IEA. *Technology roadmap – carbon capture and storage*, Paris, 2009 (available at www.iea.org/papers/2009/ccs_Roadmap.pdf)

[12] Pearce JM, Hannis SD, Kirby GA, Delprat-Jannaud F, Akhurst MC, Nielsen C, Frykmann P, Dalhoff F. How to submit a CO_2 storage permit: Identifying appropriate geological site characterisation to meet European regulatory requirements, *Energy Procedia*, 2013; this volume.

[13] Ramirez A, Hagedoorn S, Kramers L, Wildenborg T, Hendriks C. Screening CO_2 storage options in The Netherlands, *Int. Journal Greenhouse Gas Control* 2010; **4**, 367 – 380.

[14] Neele F, Delprat-Jannaud F, Vincké O, Volpi V, Nepveu M, Hofstee C, Wollenweber J, Lothe A, Brunsting S, Pearce J, Battani A, Baroni A, Gacia B. *Draft site characterisation workflow*, SiteChar report D1.2, 2012.