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How to submit a CO_2 storage permit: Identifying appropriate geological site characterisation to meet European regulatory requirements.

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Abstract

EU Member States are in the process of transposing European regulatory requirements that define the high-level conditions of a storage permit into their national laws. This regulatory framework defines a range of performance standards which recognise specific high-level uncertainties and long-term issues which storage developers will have to address. However, with one or two notable exceptions, the level of site characterisation required to obtain a storage permit has not been systematically evaluated.

To determine the required geological site characterisation necessary to demonstrate adequate understanding of site performance, two storage case studies identify those issues that might remain challenging in the permitting process. These case studies, an onshore aquifer and an offshore multi-store site, produce credible dry-run storage permit applications from site geological characterisation activities, which are evaluated by a separate team, acting as a regulator. The applications, though necessarily reduced in scope from those anticipated for full storage projects, comprise the key elements of a permit. Issues identified during this process include:

- Defining the storage complex boundaries, which for certain sites may be challenging, especially where expected pressure responses may extend for some distance or where lateral boundaries may not be clearly defined. We present examples of how these regulatory boundaries have been defined for the two case studies.
- Key Performance Indicators (KPIs) include a range of metrics against which site performance can be measured, both during the operational and closure phases, providing a basis for the design of the geological monitoring program and the corrective measures plan. Defining qualitative terms such as ‘sufficient’, ‘expected’ or ‘acceptable’ in appropriate quantitative metrics has been attempted for site-specific KPIs in the case studies described. Whilst it might be relatively straightforward to define qualitative indicators, we conclude that KPIs will need to be defined quantitatively for them to be the most effective.

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1. Introduction

European regulations for CO_2 storage, in particular the requirements for obtaining a permit to inject CO_2, remain largely untested in many jurisdictions, despite a number of demonstration projects undertaking site characterisation activities. To date only one permit application has been submitted, which was on behalf of the ROAD project in the Netherlands, one of the more advanced demonstration projects in Europe. A partial application was submitted for the storage site for the ROAD project in which some sections were not completed. It may be a number of years before full permit applications are made in many member states as demonstration projects undertake detailed site characterisation. This research therefore aims to assess the permitting process by developing 'dry-run' permit applications for two technically credible storage options, albeit within the resource limitations that a research-scale project imposes.

The principle objective of this research, undertaken within the SiteChar project, is to test the EC regulations for storage permitting and evaluate a preliminary site characterisation workflow [1]. In order to determine the extent of site characterisation required to submit a storage permit, draft permits for two storage sites have been developed and evaluated. Although these dry-run permit applications are conceptual, in that in the short term they are not expected to lead to real applications for storage, the permit applications are based on sites which provide credible examples of future storage options that will be required after the planned demonstration phase. This allows us to evaluate some of the more challenging aspects of the storage permitting requirements, without the constraints of a commercial project. The sites selected are a depleted hydrocarbon field and surrounding saline aquifer in the Captain Sandstone of the Outer Moray Firth, UK North Sea and the Vedsted onshore saline aquifer structure, near the city of Aalborg, Denmark.

The Outer Moray Firth site investigates a multi-store concept which anticipates storage in a depleted hydrocarbon field reservoir and the adjacent brine-filled aquifer within the Lower Cretaceous Captain Sandstone Member of the Wick Sandstone Formation. Sealing is facilitated by mudstones and siltstones of the Rodby, Carrack and Valhall formations. Two injection scenarios, with initial injection into the field or aquifer, were evaluated to determine the best approach to exploiting this capacity. Informal discussions with national regulators allowed further evaluation of key issues.

The second case study extends existing investigations of site characterisation at the Danish Vedsted site to develop a 'dry-run' storage permit application. This site is an onshore Upper Triassic-Lower Jurassic aquifer situated in a small graben which is part of a larger graben structure, the Triassic rift system forming the deep Fjerritslev Trough. The reservoir is a marine to fluvial sandstones sealed by a thick interval of marine claystone of the Jurassic Fjerritslev Formation.

2. Methodology

Development of the exemplar storage permit applications was undertaken by two teams operating independently of a third, regulatory team. Although it is recognized that the lack of resources restricts the level of detail that can be achieved in these applications relative to that necessary for aindustrial scale project, the applications attempt to address as many regulatory requirements as possible, particularly when these require information produced during initial geological site characterisation (Table 1).

Storage permit applications were developed within the regulatory framework provided by the European regulations as defined in the Storage Directive (SD) [2] and its UK and Danish transpositions.

Guidance documents produced by the European Commission (EC) and the UK's regulator, the Energy Development Unit within the Department of Energy and Climate Change, were also reviewed to ensure applications were as credible as possible. To facilitate early discussions between the applicant and regulator teams, interim applications were produced for both storage sites which summarized the results of the geological site investigations and highlighted the key risks and uncertainties that had arisen at that point (Table 1). The interim application therefore focused primarily on a geological description of the storage site and set out the initial scope for the storage project design, upon which evaluations of injectivity, dynamic storage capacity and long-term performance would be based. Review of these interim licence applications by the regulatory team will help the development of the final ones. In this paper we discuss the conclusions derived from the interim application and its review. Significant further assessment is currently being undertaken to develop final applications but that work is not discussed here.

The permit applications comprise a detailed desk-based geological site characterisation which evaluates primary and secondary containment options, static storage capacity estimates and seal integrities. Identification, assessment and prioritisation of key risks is undertaken early to facilitate site-specific evaluation of short- and long-term storage behaviour. This includes development of a risk register and definition of Key Performance Indicators (KPIs), which enable consideration of mitigation options that can be included in the project design. Other components of the dry-run permits relate to the management of residual risks and include the storage monitoring plan, together with some consideration of contingency and corrective measures and the post-closure plan.

Table 1. Contents list of dry-run storage permits

Licence application content	Interim application	Final application
1. Name and address of proposed operator	✓	
2. Appraisal term	✓	
3. Project description		
i. Injection parameters and project concept	✓	
ii. Storage development plan including:		✓
• Injection & Operating Plan		✓
• Storage Performance Forecast		✓
4. Site description		
i. Boundaries	Draft	✓
ii. Site geology, hydrogeology…	✓	
iii. Past development history	✓	
iv. Storage capacity estimate	Static	Dynamic
5. Measures to prevent significant irregularities		
i. Risk register	✓	✓
ii. Plan of risk mitigation and management of uncertainties	Draft	✓
iii. Dialogue with stakeholders	Draft	✓
6. Monitoring plan		✓
7. Corrective measures plan		
i. Performance indicators	✓	
ii. Corrective measures plan (provisional)		✓
8. Post-closure plan		

i. Performance indicators	✓	
ii. Post-closure plan (provisional)		✓
9. Environmental Impact Assessment		
i. Description of relevant features		✓

As the objective is to develop a robust geological site characterisation methodology, several topics that would be included in a full permit application are considered out of scope for the purposes of this exercise. Topics considered beyond of the scope of this exercise therefore include:

- Transport and injection infrastructure design, including the wellhead and injection well(s).
- Provisions relating to the acceptance and injection of CO_2.
- Details of financial security.
- Detailed, albeit provisional, post-closure plan. However, some discussion of performance indicators that enable site closure have been developed.
- Provisions for reporting to regulators.
- Full Environmental Impact Assessments. However, some baseline information will be produced and analysed, including a description of relevant features.
- Detailed corrective measures are not developed for some key risks that may feature in fully developed storage permits. For example, detailed technical descriptions of well remediation are not included. Nevertheless, definition of performance indicators has been undertaken that define limits beyond which corrective measures will be implemented.

2.1. Storage permit development

The storage permits were developed as follows:

1. A storage permit template was developed by the regulatory team and then agreed with the permit development teams for the Outer Moray Firth and Vedsted sites. The permit template provided a contents list of key documents and evidence required for a storage permit, as far as could be determined from published regulations.
2. Available geological data was acquired, collated and analysed to produce a static geological model of each site. Although new geological data, such as high resolution seismic data, was not acquired, significant amounts of existing data, at a range of scales and resolutions was interpreted.
3. A fundamental first step was to develop a risk register, to ensure adequate characterisation of a storage site and to develop a robust and defensible permit application. Although only a summary of the risk assessment is required within the permit regulations, the early assessment of risks, focused primarily on geological uncertainty and containment, was needed to define the key issues to be addressed by subsequent simulations and studies to address the issues required for the permit application.
4. An interim permit application was developed for each site, based primarily on the project concept defined by the results of the static model development and associated desk-top geological site assessment activities. This interim application (contents listed in Table 1) defined the principle objectives of the storage project. Permit development was undertaken independently at each site as it was intended that differences in approach would increase the value of the dry-run exercise. Interim applications were planned to provide an indication of technical issues that might arise early in the site characterisation process so that their resolution, or otherwise, during development of the final permit application could be tracked. The interim applications also helped to foster a strong dialogue between the "operator" and "regulator" at the respective sites. The issues highlighted included risks identified during initial risk assessments and geological uncertainties

arising from either a lack of site data or those that would be addressed during subsequent predictive modelling assessments. Inevitably some uncertainties would require further explorative site characterisation and testing which was beyond the resources available in this research, but their identification is still an important outcome.

5. Both interim permit applications, though only partially complete (as indicated in Table 1), were submitted to the regulatory team for review. Reviews focused on providing technical challenge on the content on the permits, in an attempt to ensure that final permit applications were supported by robust and defensible technical evidence of the sites' suitability for permanent and safe CO_2 storage. Further reviews have also been performed by an external regulatory advisory body, comprising representatives of industrial storage operators and technical evaluators from other European and Australian regulatory jurisdictions. Reviews were returned to the site characterisation teams to support development of the final storage permit applications.
6. Assessments of storage site performance are being undertaken to establish, as quantitatively as is possible, the longer-term performance of the site. These predictive assessments, based on the initial static geological models, address in more detail the key issues identified during the risk assessment processes.
7. Final dry-run licence development, following completion of storage performance assessments, includes definition of the storage complex boundaries, estimates of dynamic storage capacity, assessment of relevant aspects of the geomechanical integrity of the storage complex, definitions of operational and post-closure performance indicators; as well as required measures to prevent significant irregularities, a monitoring plan and a provisional post-closure plan.
8. An independent review of the final dry-run permit applications will elucidate the key lessons from testing of the regulatory process and the SiteChar characterisation methodology [1].

3. Sites

3.1. Vedsted

A possible geological storage site, the Vedsted structure, was identified close to Vattenfall's a coal-fired power plant, Nordjyllandsværket, near Aalborg in Denmark. Plans for the demonstration project were stopped in 2011, as Danish regulations do not support onshore storage at least until 2020. The Vedsted structure has been previously identified by GEUS as a possible geological structure suitable for safe geological storage of CO_2 [3]. The structure has been characterised from two oil exploration wells (Haldager-1, 1950 and Vedsted-1, 1958) and regional seismic lines (acquired in 1967 and 1983) and is an anticlinal closure within a fault block. The closure includes several sandstone reservoirs of good quality at depths of 1200-2000 m and a several hundred meters-thick claystone interval provide a potential caprock above the reservoirs. The Gassum Formation forms the primary reservoir and the shallower Haldager Sandstone is identified as a secondary reservoir. In addition, the underlying Skagerrak Sand Formation might have some upside storage potential. A thick chalk section is expected to provide a secondary seal. The static storage capacity of the Vedsted structure has been preliminarily estimated as 161 Mt of CO_2 based on a review of existing data. In order to verify the closure of the anticline structure, the existence and location of the bounding faults together with the storage capacity and reservoir quality, a new 2D seismic survey was acquired by Vattenfall in 2008.

The storage project concept being investigated for the dry-run permit application is to store annual emissions of approximately 1.8 Mt from the Nordjyllandsværket power station together with a further 0.8 Mt from a nearby cement factory. The distance from Nordjyllandsværket to the Vedsted structure is approximately 30 km and the CO_2 is likely to be transported by pipeline. Injection is proposed to start in

August 2020, with a minimum operating duration of 40 years, providing an expected total storage of approximately 104 Mt. Due to the initial sparse data coverage for the aquifer in the Vedsted structure, it seems reasonable to develop the storage site in several phases. Three injection wells are assumed to keep the injection rate below 1 Mt/year, which may be needed due to the relatively low permeability sandstone formation. The injection rate will be gradually increased, starting with a single well to monitor the early reservoir response data for incorporation in the reservoir modelling.

A static model, derived from the seismic interpretation includes five key surfaceslisted from top to bottom: Base Chalk Group, Top Haldager Sand Formation (Base of complex seal), Base Haldager Sand Formation (Top of primary caprock), Near Top Gassum Sand Formation (Top of reservoir) and Near Top Skagerrak Sand Formation (Base of reservoir). The storage complex boundary was defined to include the secondary storage formation in the Haldager Sand Formation.

A risk register of 22 discrete hazards were previously identified that were grouped into seven categories: reservoir, vadose zone, surface, wells, fault zones, atmosphere and regional risks. Three major risks were identified: an abandoned well, the need for more detailed characterisation of the Gassum reservoir; and the need for improved understanding of fault properties. An assessment of potential safeguarding measures that could be applied (carried out prior to this study) indicates that all of these identified risks can be reduced in terms of either probability and/or consequence. The risk of leakage via an abandoned well remained categorised as having high potential consequence and high probability.

3.2. Outer Moray Firth

The CO_2 storage project anticipates demonstrating CO_2 storage in a depleted hydrocarbon field in the Outer Moray Firth and in the surrounding saline aquifer, principally the Captain Sandstone Member of the Wick Sandstone Formation. It is envisaged that CO_2 will be injected into the saline aquifer, down-dip and beyond the extent of the field. Residual trapping and dissolution is expected to occur as it migrates up-dip through the aquifer into the hydrocarbon field where it will be structurally and stratigraphically contained by the sealing formation. Injection will continue to allow CO_2 to fill the field and then spill beyond its boundaries for storage in the wider saline aquifer. Here it is anticipated to be trapped structurally beneath the regional seal rocks and retained along the migration route by residual trapping and dissolution within pore spaces of the sandstone.

The Captain Sandstone contains highly porous and permeable sand facies and extends across an area of at least 3,400 km^2 in the Moray Firth region of the UK Northern North Sea. Characterisation and calculation of storage capacity by dynamic modelling of CO_2 injection suggests a potential capacity of more than 360 Mt for the Captain Sandstone saline aquifer [4]. It is overlain by and contained within the regional seals of the Rodby, Carrack and Valhall formations. It also hosts several hydrocarbon fields (Captain, Blake, Atlantic and Cromarty are four closest to the area of interest).

Initial project design considers development of the site as a component of Scotland's offshore storage capacity. CO_2 will be initially sourced from a single gas-fired power station source (demonstration scale) from onshore eastern coastal Scotland. Further, commercial-scale CO_2 injection will be sourced from either full capture from a single coal-fired power station or from multiple industrial sources, subject to detailed site-specific dynamic estimates of storage capacity. (In 2006, around 20 sources that annually emitted more than 100 000 tonnes of CO_2 were identified in onshore eastern coastal Scotland [4]). Injection rates will be optimized via reservoir modeling and consideration of injection locations, injectivity and dynamic capacities.

The Storage Complex is a defined volume that extends beyond the Storage Site and is defined by the envelope of the maximum extent of the CO_2 plume suggested by dynamic modelling and includes:

- The primary seal to the Storage Site: the mudstones of the Valhall, Carrack and Rodby formations. Rocks of the overlying Chalk Group may also act as seal if they are of sufficiently low permeability.
- Secondary reservoirs for CO_2: This will be provided by strata overlying and laterally continuous with the Storage Site that may be hydraulically connected. These include possible lateral continuation of the Storage Site reservoir within the Coracle or Punt sandstone members of the Wick Sandstone Formation and any rocks with available pore volume that overlie the primary seal (should it be breached); for example the rocks of the Chalk and Montrose Groups.
- Secondary seals (to the secondary reservoirs): the mudstone parts of the Lista Formation of the Montrose Group and the mud-prone Moray Group.

An expert workshop, and subsequent geological interpretation, identified 79 risks within five categories: containment; adverse effects on other resources; reduced technical performance; monitoring and regulatory; and economic/environmental risks. These were ranked according to their estimated severity and probability. At this stage the risks were 'unmitigated'. The highest risks were then investigated further to see if they could be mitigated, i.e. if further investigations enabled estimates of their probability or severity to be reduced, or at least identified subsequent actions that would reduce the risks. Two of these *unmitigated* risks relating to leakage up abandoned or new injection wells, were judged to be high probability and high severity risks. A further six relevant unmitigated risks were judged to have high severity and medium probability; of these, two relate to the potential high costs if capacities are too low, one relates to the potential for no or poor secondary seals at the storage complex boundary, two relate to stakeholder opposition (hydrocarbon field operators and the public), and a risk of limited connectivity within the Captain Sandstone Member. A further four *unmitigated* risks were judged to have medium severity but high probability: (unpredicted) preferred lateral pathways focussing flow e.g. vertical barriers present or higher permeability zones; pressure interference in hydrocarbon fields; inability to accurately determine residual hydrocarbon distribution and saturation for input into modelling; and a thin or absent primary caprock.

These identified risks were used to direct subsequent predictive assessments of the dynamic storage capacity, the potential pressure responses during injection and its impacts on caprock integrity, the detection limits for seismic monitoring and the assessment of mechanical well integrity.

4. Key issues for the development of the storage permit applications

A number of issues have required resolution during the development of the permit applications for the Outer Moray Firth and Vedsted sites. An early requirement was the definition of storage complex boundaries. The SD, and the UK transposition of this, defines the storage complex boundary as: *"...the storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations"*. This is a fundamental step in defining the leased volume for exploration, including injection tests if appropriate, for evaluation of the operational and post-closure storage performance and these boundaries define the volume of geosphere that, as a minimum, will be monitored (SD Article 13). Importantly, the complex boundary is also used to define CO_2 leakage, such that any migration of CO_2 beyond it is defined as leakage. However supporting guidance documents [e.g. 5], suggest that exploration of the area surrounding the storage complex may also be required, though this is not implied in SD Article 5. Whilst the methodology to define the extent of the storage complex is not explicitly proposed in the SD, here we have taken this to be the maximum extent of the predicted CO_2 plume migration. An operator may prudently add a small buffer zone to this extent within the reservoir to allow for discrepancies between initial predictions of plume migration and observations. It is recognized that the pressure response, when injecting into saline aquifers or repressurised depleted hydrocarbon fields, may extend beyond this defined complex volume. However, defining complex boundaries on the basis of a pre-defined pressure threshold is not considered practical, although potential impacts, such as pressure effects on nearby active hydrocarbon fields, would still need to be taken into account. A consequence may be requirements for pressure monitoring outside the storage complex and potentially water production for controlled pressure release.

Storage permits will contain conditions for site operation and, importantly, it is assumed at least provisional conditions for site closure. Both operator and regulator will require as much certainty about these conditions as possible. In particular, in order to take final investment decisions, project developers are likely to need confidence that if site performance meets the applied conditions, they will continue to be granted permission to inject and, importantly, at the end of the project, they will be able to close the site and transfer liability back to the Competent Authority (CA). In addition, the CA will require confidence that site performance can be adequately monitored and that clear evidence of safe performance leading to permanent containment can be provided. For these reasons we consider that the definition and agreement of key indicators for site performance will be fundamental to the site permitting process. The interim permit applications developed for the Vedsted and Outer Moray Firth sites contain a number of qualitative permit performance conditions (PPCs) that reflect the regulatory requirements and also the specific site characteristics (Table 2). However, in many cases we believe that these qualitative KPIs will require more quantitative definitions. Quantitative PPCs will, of course, be defined from the predictions of site performance based on the geological site characterisation and on the ability of applied monitoring to provide reliable quantitative information. In some cases PPCs will be defined by a range of values. If monitoring indicates an agreed parameter is outside the agreed range or threshold value, then it is assumed that this would be determined as a significant irregularity and the appropriate actions taken as defined in the operator's corrective measures plan. Discussions are ongoing with regulators and operators to determine an appropriate method of defining PPCs.

Table 2: Qualitative permit performance conditions (PPCs) for the Outer Moray Firth site as defined in the interim storage permit application.

PPC	Description	PPC	Description
PPC-1	No injected CO_2 detected outside complex (*i.e. no detectable leakage).* • In rocks overlying complex (i.e. in overburden) • At wellheads • At sea bed • In atmosphere	PPC-5	Geomechanical integrity of site will be maintained KPI-5.1 Injection pressure will not exceed specified amount KPI-5.2 No detrimental induced seismic activity leading to a significant irregularity or leak • Within the Storage Site • Within the Storage Complex • Within the monitoring area (if this is larger than complex) (i.e. in overlying or lateral rocks) KPI-5.3 No detrimental seabed uplift/ground displacement (i.e. it will remain within predefined limits)
PPC-2	Pressure and temperature changes will remain within predefined/predicted ranges • Within the Storage Site • Within the Storage Complex • Within the monitoring area (if this is	PPC-6	Geochemical changes in fluid composition will be within predefined ranges • Within the Storage Site • Within the Storage Complex • Within the monitoring area (if this is larger

	larger than complex) (i.e. in overlying or lateral rocks)		than complex) (i.e. in overlying or lateral rocks)
PPC-3	CO_2 plume will not migrate beyond storage site	PPC-7	No adverse environmental or human health effects due to operation • At sea bed / in water column • In atmosphere
PPC-4	CO_2 plume shows migration within expected modelled behaviour	PPC-8	Cost per tonne of CO_2 will remain within set limit

5. Summary

Exemplar permit applications have been developed for two possible CO_2 storage sites to test a site characterisation workflow and determine the level of site knowledge required to successfully obtain a permit to store under EC regulations. These sites, an offshore site in the Outer Moray Firth, UK and an onshore site near Aalborg in Denmark, provide case studies that illustrate the issues that are likely to require addressing for similar sites. Although the site characterisations are limited predominantly to desk studies and analysis of existing data, it is clear that the risk assessment process can identify the priority areas of uncertainty to focus further site characterisation. Many of the identified risks can be mitigated during the storage design stage and those that remain relatively high are likely to be closely monitored during the operational and post-operational phases.

Key Performance Indicators (KPIs) are likely to be fundamental to the storage permit in providing a list, agreed by both operator and regulator, of both qualitative and quantitative measures of site performance. Meeting these KPIs will allow both continued storage and importantly site closure and subsequent transfer of liability from operator to competent authority. We provide some initial results on the nature and scope of these KPIs.

Finally, we have examined how storage complex boundaries can be defined. The definition of this boundary is necessary for several reasons but most importantly because movement of CO_2 beyond it is defined as leakage by the Storage Directive. Here we propose that this boundary could be defined primarily by the maximum expected extent of plume migration, rather than including the pressure responses that might be observed beyond this point.

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