Storage Readiness Levels: communicating the maturity of site technical understanding, permitting and planning needed for storage operations using CO_2

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Abstract

A framework of Storage Readiness Levels (SRLs) is presented to communicate the entirety of technical appraisal, permitting and planning activities achieved at a potential CO_2 storage site and what remains to be completed for CO_2 storage operations. The schema, based on learning gained from the experience of researchers, regulators and industry from the 1990s, is described and assessed by application to 742 saline formation and hydrocarbon field sites, offshore the UK, Norway and The Netherlands. The framework is flexible to accommodate national differences in procedures and practise and the unique character of each site. It is applicable regardless of the time-scale of appraisal or scale of assessment. The framework is consistent with and extends the industry commercial project development classification to include categories for sites with a lesser level of data and evaluation. Application to the phases of appraisal of three sites illustrates that investigations may advance understanding by different pathways and rates. The standardised framework enables comparison of the experience of permitting and planning activities completed within different jurisdictions, the level of investment and the duration required to achieve permitted or permit-ready sites. It is intended that the framework of SRLs should be widely applied.

Keywords
CO_2 storage site maturity; Storage Readiness Levels.

1 Introduction

This paper presents CO_2 Storage Readiness Levels (SRLs), a schema to communicate maturity of understanding of a site for the geological storage of CO_2 and what remains to be achieved for it to become operational. The schema is based on learning gained from the experience of the UK, Norway and The Netherlands from the 1990s. Each of these three countries has investigated potential storage sites to differing levels of understanding within their national jurisdiction. Industry and regulatory stakeholders have sought guidance on the maturity of understanding of sites within their national jurisdictions to judge which are best understood and most advanced for CO_2 storage operations. The CO_2 Storage Resources Management System (SRMS) presents a standardised assessment of commercial CO_2 storage (SPE-SRMS, 2017). The commercial industry project remit of the SRMS, however, results in a focus on the stages of site study and development for CO_2 storage that are closer to site operation. In an assessment of a regional or national geological storage resource for strategic development, as may be undertaken by a national geological survey or research organisation, the SRMS is of limited value, as it lacks granularity in these first phases of storage feasibility assessment. Maturity of understanding and levels of appraisal, as well as quality of available data, have been considered in the compilation of CO_2 storage atlases around the globe. The high-level mappings found in these atlases are usually focused on identifying sedimentary basins where exploration for storage resources for a region or country's potentially captured CO_2 is likely to be successful. The maturity of storage resources may be indicated by placement in a storage resource pyramid (see. e.g. Bradshaw et al., 2007) and the amount and quality of data may be indicated through the use of a Boston square analysis (Norwegian Petroleum Directorate, 2014; Cavanagh et al., 2020). This kind of characterisation is, however, less focused on describing remaining work until a prospective site can be described as 'discovered' in the SRMS.

Neither the SRMS classification or the maturity appraisals of CO_2 storage databases/atlases convey what has been achieved and what remains to be undertaken to CO_2 storage stakeholders unfamiliar with CO_2 storage permitting and CCS project planning. Here we present a schema of CO_2 Storage Readiness Levels (SRLs) to communicate technical understanding, progress toward regulatory requirements for CO_2 storage and injection, and planning of a site as a component of a commercial CO_2 storage project. The objective is to convey a common understanding to technical and non-technical stakeholders alike of the technical appraisal of a site, achievement of permits, and planning for a CO_2 storage project. The schema is designed to complement and exist alongside the industry SRMS classification, building on hydrocarbon industry knowledge and practice, since such expertise and assets are anticipated for commercial implementation of CCS. We believe and hope the SRL communication schema, developed from the experience in Europe, can be applied to describe maturity of understanding of storage sites in other settings and regions of the world.

1.1 Background

Methodologies for assessing CO_2 storage capacity by research groups worldwide have addressed the challenge of creating a unified method for calculating potential storage volumes, e.g. Bachu et al. (2007), Bradshaw et al. (2007) and Gorecki et al. (2009 a, b). However, storage capacity estimations alone do not consider all factors that influence feasibility of a prospective site for an operational CO_2 storage project. These include technical factors, such as data availability, data interpretation, appraisal for CO_2 containment and injectivity, and non-technical factors including ownership, regulatory regime, available CO_2 for storage, and prior planning and permitting, as the storage component of a CCS project.

The Global CCS Institute's CCS readiness index (Consoli et al. 2017, and subsequent annual updates) is a high-level analysis applied country by country to rank major barriers and enablers for CCS deployment. The index quantifies national interest, policy, legal and regulatory frameworks and maturity of storage resource assessment on a national level. It is therefore better suited to the level of assessment typically found in storage atlases, rather than to communicate the level of maturity and expected work remaining for an operational storage site or group of sites.

Assessment of the viability of geological CO_2 storage resources as commercial prospects has been considered alongside the earliest classifications of storage capacity. Bradshaw et al. (2007) applied economic, legal and regulatory constraints to define techno-economic categories to storage capacity assessment. The concepts of resources and reserves were introduced by Bachu et al. (2007). Gorecki et al. (2009 a, b) classified storage capacity assessment and incorporated techno-economic categories with resource appraisal to define and apply categories of resource and capacity specific to CO_2 storage.

Gorecki et al. (2009 a, b) introduced certainty taking an approach familiar from resource evaluation, based on previously published techno-economic resource classifications and definitions (Bachu et al., 2007; PRMS, 2007; US DOE NETL, 2008; IEA GHG, 2008), to define categories of proved, probable and possible effective storage capacity. More recently, the Society of Petroleum Engineers presented the SRMS by adaptation of the petroleum resource management system (PRMS, 2011), following the practise of the hydrocarbon industry (SPE-SRMS, 2017).

Application of the SRMS (SPE-SRMS, 2017) to the UK and The Netherlands national CO_2 storage databases places the vast majority of the storage units within a single category. More than 550 UK and 100 Netherlands storage units are classified as undiscovered storage resource, despite the differing levels of understanding from research investigations of feasible CO_2 storage project concepts by industry and academia. The SRMS classification does not reflect the range of maturity of understanding and assurance of capacity and containment of the storage units classified as ‘undiscovered' storage resource.

2 Methodology

The practice of communicating progress from basic principles to fully operational, is widely accepted in technology development as Technology Readiness Levels (TRLs) and a similar terminology of CO_2 Storage Readiness Levels (SRLs) was adopted. The basis for the definition of the SRL schema is the CO_2 storage site appraisal and CCS project planning and operation conducted in the UK, Norway and The Netherlands. Publicly available academic and industry storage site appraisal research and inventories of potential CO_2 storage sites in each of the three countries, hereafter referred to as ‘national storage portfolios’, were reviewed. These comprise a total of 742 prospective sites, offshore saline aquifer formations and hydrocarbon field sites in the UK CO_2Stored database (Bentham et al., 2014), Norwegian Petroleum Directorate CO_2 Storage Atlas (Norwegian Petroleum Directorate, 2014) and national inventory study (Vangkilde-Pedersen et al., 2009; EBN Gasunie, 2017) in The Netherlands. Publicly available Front-End Engineering and Design (FEED) studies for CO_2 storage projects in the UK and The Netherlands, and the experience of the operation of storage sites in Norway were also reviewed. The European regulatory requirements, as well as procedures and practise for permitting of CO_2 storage operations and CCS projects in each country, were considered. The review benefitted from the contribution of first-hand experience of the authors, as providers of national geoscience information and research institutions for CCS and learning gained from the appraisal and planning of CO_2 storage sites and site operation in Norway.

The technical CO_2 storage site characterisation, risk assessment and risk reduction, regulatory permitting and CCS project planning activities for the inventory of sites were evaluated. The entirety of site characterisation effort was considered.

The evaluation included but was not restricted to consideration of:

- Level of confidence in storage capacity, i.e. storage capacity assessed and verified;
- Gathering, use and interpretation of existing data, e.g. seismic data, exploration and static geological models;
- Acquisition of new data, although it is not an expectation that all potential storage sites need to acquire new data, in some cases existing data will be sufficient;
- Application for, and issue of permits required for CO_2 storage;
- Identification of risks to the secure containment of CO_2 at a storage site;
- Mitigation or management of any identified risks to secure containment at a storage site.

The evaluation considered the level of characterisation and technical appraisal activities needed for each SRL. Existing published classifications (e.g. Bachu et al., 2007; Bradshaw et al., 2007; Gorecki et al., 2009 a, b; SPE-SRMS, 2017), methodologies and schemas (e.g. Groenenberg et al., 2008; Akhurst et al., 2015; Delprat-Jannaud et al., 2015; Nepveu et al., 2015; Nielsen et al., 2015), assessments (IEA GHG, 2008), regulations and regulatory guidelines (EC, 2009; EC 2011), findings reported from CO_2 storage research projects (e.g. SCCS, 2015) and publicly available storage project documents and plans (e.g. Baklid et al., 1996; Maldal and Tappel, 2004; Arts et al., 2012; Loeve et al., 2014; Mikunda et al., 2015; National Grid, 2016a; Pale Blue Dot, 2016; Shell, 2016c; ROAD, 2018) were considered to ensure the SRLs were consistent and complementary.

The activities were ordered and placed into groups that can be applied regardless of the different terminology used and regulatory CO_2 storage procedures in each country. SRLs were drafted, discussed and compared with the experience and activities taken to plan and permit storage sites in the three countries. Nine SRLs were defined after iterative discussion and revision (Figure 1, Table 1).

The definition of the SRLs benefited from application to offshore sites in the three national storage portfolios and also from feedback from a panel of European regulators and international industry stakeholders. Where appropriate, equivalences were drawn with the CO_2 SRMS (SPE-SRMS, 2017) and common terminology used. The effort and level of resources needed to advance a storage site to full operation as a component of a CCS project was also assessed. Storage site appraisal has been conducted since the 1990s and permitting and operation of storage sites in the North and Barents seas for more than 20 years. Estimates in published papers and publicly available reports of the investment in storage site appraisal and CCS project planning and its duration were reviewed and compared to the SRLs achieved for European storage sites. Publicly available FEED studies for CO_2 storage projects in the UK and the Netherlands, and the experience of the operation of storage sites in Norway were also used to inform duration and cost.

3 Description and application of SRLs

Permitting, planning and indicative appraisal activities for saline aquifer and hydrocarbon field storage sites by SRL are summarised in the following sections, and in Figure 1 and Table 1.

SRL number	Description/title of SRL	Stages and thresholds in the storage site permitting process	Stages and thresholds in technical appraisal & project planning
SRL 1	First-pass assessment of storage capacity at coutry-wide or basin scales	Gathering information for an exploration permit, if needed*	Technical appraisal
SRL 2	Site identified as theoretical capacity		
SRL 3	Screening study to identify an individual storage site & an initial storage project concept		
SRL 4	Storage site validated by desktop studies & storage project concept updated		
SRL 5	Storage site validated by detailed analyses, then in a ‘real world’ setting	Exploration permit Planning & plan iteration for a storage permit ♦	Well confirmation, if needed* Outline planning for development
SRL 6	Storage site integrated into a feasible CCS project concept or in a portfolio of sites (contingent storage resources)		Technical risk reduction completed Project planning & permitting iterations
SRL 7	Storage site is permit ready or permitted	Storage permit♦ application & iteration	
SRL 8	Commissioning of the storage site and test injection in an operational environment	Storage permit♦required Injection permit application, if needed	All planning work completed Construction & testing
SRL 9	Storage site on injection	Injection permit	Site construction completed Operation & monitoring

♦ Equivalent of storage permit relevant to national jurisdiction

Figure 1 SRLs framework, stages and thresholds in the storage site permitting process and storage project technical appraisal and planning (green). The thresholds for permitting are illustrated and labelled in brown. The technical appraisal and planning thresholds are illustrated and labelled in green. *An exploration permit or well confirmation may not be needed for re-use of a hydrocarbon field for CO_2 storage.

Table 1. Descriptive title, and activities that are likely to have been undertaken, from initial capacity assessment to project operation, by Storage Readiness Level (SRL). EIA, Environmental Impact Assessment.

SRL	Descriptive title	Activities likely to have been undertaken at each SRL
SRL 1	First pass assessment of storage capacity at country-wide or basin scales	At SRL 1 an appraisal to identify the CO_2 storage potential has been completed, as a first pass assessment, although this potential may not have been fully quantified. Characteristics suitable for CO_2 storage have been identified within an area, country or region.
SRL 2	Site identified as theoretical capacity	At SRL 2 there has been assessment of the storage potential by systematic mapping of an area, whole region, country or jurisdiction's potential storage resource. A consistent and referenced methodology will have been followed and applied to calculate the theoretical storage capacity.
SRL 3	Screening study to identify an individual storage site and initial storage project concept	At SRL 3 a screening study will have been completed, achieved after a ranking exercise based on the storage site's expected performance against a set or subset of geological, technical, economic and geographical criteria. An initial project concept will have been outlined and a CO_2 storage site may have been identified, either individually or as a group of sites, as having high potential for storage. Any major risks to containment and capacity will have been identified.
SRL 4	Storage site validated by desktop studies and storage project concept updated	At SRL 4 a detailed desktop characterisation of the storage site will have been completed to validate the selection as potentially suitable for storage. For a site to qualify for SRL 4 it will have an initial static geological model or conceptual geological model. Available site-specific data will have been interpreted. There is sufficient information for preparation of an exploration licence application and submission to the relevant authority, if needed.
SRL 5a 5b 5c	Storage site validated, firstly, by detailed analysis, then in a relevant 'real world' setting	At SRL 5a detailed risk assessment-led investigations and risk reduction activities required to inform a storage permit application specific to a given site based on existing information will have been completed. At SRL 5b new data is acquired, where needed, to assure the storage site, this may include direct evidence of the storage strata, or equivalent structure or site, and to inform an EIA. Well test data will have been acquired and/or assessed. At SRL 5c all storage site data will have been acquired, analysed and technical appraisal completed to reduce or mitigate storage risks to an acceptable level and sufficient for a storage permit application.
SRL 6	Storage site integrated into a feasible CCS project concept or portfolio of sites (contingent storage resource)	At SRL 6 a storage site will have been integrated into a feasible CCS project or a portfolio of sites. The assured storage capacity will have been defined. An EIA will have been completed. All concerns regarding subsurface containment, migration and capacity to store CO_2 for a project will have been addressed.
SRL 7	Storage site is permit ready or permitted	At SRL 7 all of the CCS project planning work, based on the technical appraisal and as required for a storage permit application, will have been completed. An application for a CO_2 storage permit has been either submitted to the Competent Authority and permitted or is ready to be submitted.
SRL 8	Commissioning of the storage site and test injection at the site	At SRL 8 the storage permit has been issued and the investment decision to construct and operate the site for a CCS project has been made. All legal and practical activities needed to implement site commissioning have been completed and the storage site has been tested in an operational environment.
SRL 9	Storage site on injection	At SRL 9 the site is operational as a component of an integrated CCS project.

3.1 SRL 1 - First pass assessment of storage capacity at country-wide or basin scales

At SRL 1 an appraisal to identify the CO_2 storage potential has been completed, although this may not have been fully quantified. Characteristics suitable for CO_2 storage have been identified within a country or region, typically by sedimentary basin. The basic criteria for identification at SRL 1 are recognition of a porous rock, sealed by a cap rock and at a depth greater than 800 to 900 metres. Entire geological formations may be identified, although not necessarily individual sites within them. The information used may include geological maps, published information and expert elicitation. The potential storage capacity identified at SRL 1 is equivalent to the SRMS total storage resource (SPE-SRMS, 2017).

3.2 SRL 2 - Site identified as theoretical capacity

At SRL 2 there has been systematic mapping of the storage potential of an area, region, country or jurisdiction's potential storage resource. A consistent and referenced methodology will have been followed and applied to calculate theoretical CO_2 storage capacity based on accepted criteria for storage sites, e.g. CSLF (2007) and US DOE NETL (2012). The assessment is a desk-based study and requires sufficient data to enable the calculation of storage capacity, such as geological maps, published data, national databases and existing publicly available seismic survey and well data. The results of large-scale mapping at SRL 2 may be presented as storage atlases of country-wide or regional storage potential. Theoretical capacity appraisals may rely on average values for storage site properties and physical characteristics. Alternatively, the assessment is based on minimum, maximum and most likely values for parameters such as storage formation porosity, permeability and thickness. In some cases, Monte Carlo simulations will then be performed to ensure statistical representation of the required parameters. The theoretical potential for CO_2 storage by area, region or country may include individual storage sites; the degree of assessment at each site will depend upon the available data. At SRL 2 a high-level identification of possible geological risks to containment of stored CO_2 may have been undertaken.

3.3 SRL 3 - Screening study to identify an individual storage site and an initial storage project concept

At SRL 3 a screening study will have been completed, achieved after a ranking exercise based on a storage site's expected performance against a set or subset of geological, technical, economic and geographical criteria. An initial project concept will have been outlined. A CO_2 storage site may have been identified, either individually or as a group of sites, as having high potential for storage. All relevant existing data and readily accessible data are compiled and interpreted at SRL 3 although only publicly available data is likely to have been used. The site or group of sites will have been considered within the context of the initial concept for a storage project. Equally, the envisaged project might comprise a site for a specific industry project, a concept for storage or a component within a national portfolio of storage provision. The SRL 3 screening study will have identified all major risks to storage. Data required to increase understanding and address 'data gaps' to mitigate or reduce risks to containment, will also have been identified. A hydrocarbon field that is well known from hydrocarbon licensing and production but has not been assessed in terms of risks to containment of CO_2, as a prospective storage site, would be at SRL 3.

3.4 SRL 4 - Storage site validated by desktop studies and storage project concept updated

At SRL 4 a detailed desktop characterisation study of a site will have been completed to validate the selection as potentially suitable for CO_2 storage. A site at SRL 4 will have an initial static geological model or conceptual geological model. All site-specific publicly available data will have been integrated and included in the desktop characterisation studies and the initial storage project concept will have been updated. Characterisation activities will be dependent on the nature of the site and available data and could involve the collation of additional site information, and efforts will have been made to access proprietary site information. The available data may have been processed or re-processed. Data collated and interpreted at SRL 4 could include geomechanical stability information, hydrogeological data, well production information, and geophysical surveys. It is essential to examine the status of all legacy wells within the storage complex (EC, 2011) including their plugging and abandonment status.

At full completion of SRL 4 there will be sufficient information to indicate if it is feasible to store CO_2 at the site and preparation of an exploration licence application, if needed. Hydrocarbon operators considering field re-use for CO_2 storage will already hold an exploitation permit and a field geological model. They are likely to have sufficient exploration and production data to inform a desktop appraisal and present a CO_2 storage project concept to achieve SRL 4. In particular, an operator will be assured of the CO_2 storage capacity of the field.

3.5 SRL 5 - Storage site validated firstly by detailed analyses, and then in a 'real world' setting

At completion of SRL 5 all iterations of risk-reduction technical analysis and appraisal work for the storage site, initiated at SRL 3, will have been fully completed. All elements of the storage project will have been modelled in a simulated environment and investigations may have been undertaken on site geological materials. Multiple realisations of dynamic flow models of CO_2 migration and geomechanical stability modelling are likely to or may have been produced, respectively. The boundaries of the storage site will have been clearly defined and included in the detailed information about the storage complex (EC, 2009, 2011). Technical appraisal will have reduced risk to subsurface containment of CO_2 sufficiently to assure injection and so definition of the storage capacity, to inform the CO_2 injection scenario for a future storage permit application. Detailed risk assessment-led appraisal is an iterative process of investigation, data acquisition, collection of new data, and analysis to reduce and mitigate all risks (Nepveu et al., 2015); a single 'cycle' is presented as SRL 5a, 5b and 5c (Table 1). The number of iterations will be specific to each site. Acquisition of new data at SRL 5b will have been to reduce critical storage risks such as: a well to confirm the presence and character of the storage and cap rock strata for a virgin saline aquifer site; well test data to assure injectivity. Hydrocarbon field operators are likely to have acquired the data needed for detailed risk assessment-led characterisation activities at SRL 5, although they may not have conducted investigations, modelling or simulations tailored for CO_2 storage. Field operators may not have assessed the role of legacy wells in CO_2 storage, including an understanding of their integrity and abandonment standard, but likely to hold well test, production test data or own wells upon which to conduct tests.

3.6 SRL 6 - Storage site integrated into a feasible CCS project concept or portfolio of sites (contingent storage resource)

At SRL 6 a storage site will have been integrated into a feasible CCS project concept or a portfolio of sites. The detailed design of the infrastructure, practical operation and the extent, timing and data to be acquired to monitor the storage site, within an integrated CCS project, will be constrained by the technical risk-assessment led investigations. A site that is part of a national storage portfolio will be assessed on reduction of risks to the assured receipt and storage of CO_2 planned to be captured from one or more sources. The assessment will address the capability to receive CO_2 at the planned capture rates supplied via a transport and storage network. An Environmental Impact Assessment (EIA) will have been completed. Hydrocarbon operators considering field re-use for CO_2 storage will be familiar with the risk assessment process and the planning, design and techniques for risk reduction and mitigation and the preparation of an EIA; field operators are less likely to be familiar with the risks specific to CO_2 injection, capacity and containment. At full completion of SRL 6 the site or sites will be considered a contingent storage resource, equivalent to and with same terminology as the SRMS (SPE-SRMS, 2017).

3.7 SRL 7 - Storage site is permit ready or permitted

At SRL 7 all of the CCS project planning work, based on the technical appraisal and as required for a storage permit application, will have been completed. An application for a CO_2 storage permit has either been submitted to the Competent Authority and permitted or is ready to be submitted subject to agreement of appropriate financial investments and terms. All plans for operation of the storage site will have been completed, including project and site descriptions, measures to prevent irregularities, monitoring, corrective measures and closure plans (EC, 2009, 2011; Delprat-Jannaud et al., 2013). Information required for a permit to operate a CCS project, such as details of financial security, reporting, notification and implementation of changes and post-closure plans and an environmental impact assessment (EC, 2009, 2011; Delprat-Jannaud et al., 2013), will also have been prepared. The planning requirements and procedures will be the same for depleted hydrocarbon fields and for saline aquifer stores.

3.8 SRL 8 - Commissioning of the storage site and test injection at the site

At SRL 8 the storage permit will have been issued and the investment decision to operate the site for a CCS project will have been made. Investment in new infrastructure and data acquisition may be required. All legal and practical activities needed to implement site commissioning, including contracting, purchasing and construction, will have been completed. At SRL 8 the storage site has been tested in an operational environment. Hydrocarbon field operators will be very familiar with the legal and practical activities for the commissioning, management and testing of infrastructure. However, they are less likely to be familiar with the conversion to injection, adaptation and implementation of CO_2-compatible hardware.

3.9 SRL 9 - Storage site on injection

At SRL 9 the site is operational as a component of an integrated CCS project. Further development of the site, for example, to increase the storage capacity at the site, would require further characterisation and testing. In European legislation an existing storage permit cannot be extended without re-submitting an entire revised permit application. When planning an extension to an existing operational site the applicant would effectively return to SRL 5. However, experience of the storage operations and monitoring data acquired for the permitted site will provide data to inform application for a revised permit, particularly where the extension is anticipated by the operator.

3.10 Application of the SRL framework to national storage resource portfolios

The framework of SRLs was assessed and tested by application to potential, prospective and operational storage sites, the national CO_2 storage resource portfolios, in the UK, Norway and The Netherlands. The technical appraisal, planning and permitting activities that had been undertaken for each site or sites at the time of assessment in 2020 were reviewed and a judgement made to assign the most appropriate SRL. The results of this assessment are summarised in Table 2 and the position of sites assessed at SRL 3 or higher are illustrated in Figure 2. Details of the assessment and application of the SRL framework on the national resources are described in Appendix A and Bentham et al. (2019).

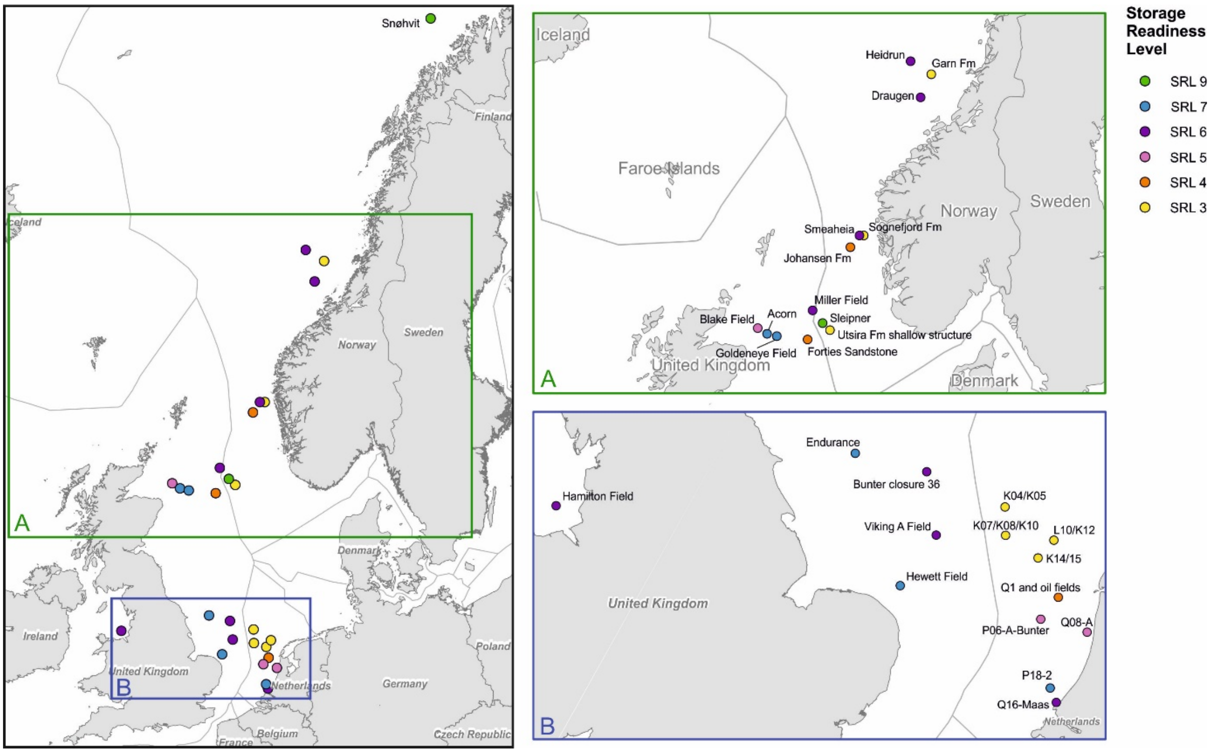

Figure 2 Map showing the position and name of prospective and operational CO_2 storage sites assessed as SRL 3 or above in UK, The Netherlands and Norwegian national waters. Inset maps: A Detail of northern UK and Norwegian sites; B Detail of southern UK and The Netherlands sites. International offshore boundaries shown in grey. Fm, Formation.

Table 2 Application of the SRLs framework to the UK, The Netherlands and Norwegian storage resource portfolios.

SRL	UK	The Netherlands	Norway
SRL 1			All sedimentary basins offshore Norway
SRL 2	All prospective storage sites in the UK national CO_2Stored database are at SRL 2 or above	All gas fields in the Netherlands assessed for CO_2 storage.	Prospective sites in aquifer formations (NPD Storage Atlas)
SRL 3	Individual storage sites and regional capacity of the Captain Sandstone formation	Gas fields in the P and Q blocks, aquifer and gas field clusters in K14/K15, K04/K05, K06/K08/K10 and L10/K12	Sites within Utsira, Garn and Sognefjord Formations
SRL 4	Two saline aquifer storage sites in the Forties and Bunter sandstones	Aquifer and oil field sites in block Q1	Johansen Formation
SRL 5	Three storage sites; Blake Field, Goldeneye Field with surrounding aquifer and Captain Sandstone saline aquifer site	Offshore gas fields Q08-A and P06-AB.	
SRL 6	Six sites; Hamilton gas field, Captain Sandstone, Forties sandstone 5, Bunter closure 36, Viking A gas field and Miller Field site.	Gas field site Q16 Maas.	CO_2-EOR in the Draugen and Heidrun oil fields and aquifer storage in the Smeaheia site
SRL 7	Four sites; Captain Sandstone (ACT Acorn Project), Hewett Field, Goldeneye Field and Endurance structure.	Cluster of three gas fields in the P18 block; P18-4, P18-2 and P18-6.	
SRL 8			
SRL 9			Sleipner (Utsira Fm.) and Snøhvit (Tubåen Fm.) CO_2 storage projects

3.11 Discussion of the framework and its application

The SRL framework of standardised levels was found to be sufficiently flexible to be applied to all the sites investigated despite the differences in procedures and experience of the three countries. The grouping of activities worked well in the three countries. This grouping follows from a common understanding in the scientific community and in the industry of the order in which different aspects of a storage site, including safe design, construction, operation and maintenance, are to be assessed (e.g. EC, 2011; ISO, 2017; CSA, 2018). The SRLs framework readily accommodated different store types, whether saline aquifer formations or hydrocarbon field sites. The activities completed or likely to be undertaken at each SRL are concomitant to the level of detailed technical appraisal, permitting and project planning activities required. Although, the work necessary to achieve a given SRL will vary between sites, due to natural variation in geology and also the amount of pre-existing data. It is implicit in the framework of SRLs that there is increased certainty in the understanding of a CO_2 storage site and deeper insight into site design and operation that minimise operational and containment risk at the higher levels.

Application of the framework emphasised the unique character of each site in terms of the geology and data types available and appropriate to characterise the site. Assignment of an SRL to a site requires a degree of judgement, as some aspects of a site may be better understood than others. For example, while assessment of the quality of a cap rock may provide a high certainty of containment, the maximum pressure increase that could be applied to create storage capacity may be less clear. The SRL should reflect the overall level of work done on a site; there will always be a certain asymmetry in the level of uncertainty regarding different aspects of the feasibility of storing CO_2 at a site. This flexibility is a strength and appropriate as a qualitative tool to communicate readiness of any site for storage operations using CO_2.

Not every storage site will start at the lowest levels when first considered for CO_2 storage. An operator of a depleting hydrocarbon field will already hold much of the data, information and knowledge needed to operate that field as a CO_2 storage site and would therefore place the site at SRL 3. Application of the SRL framework is not constrained by time- or geographical scales. It is relevant to a gradual strategic approach, a rapid assessment and permitting driven by a requirement to reduce emissions or re-use a hydrocarbon field asset. The SRL framework can be applied at a wide range of scales; from national scale (e.g. Norwegian Petroleum Directorate, 2014) to local scale in the vicinity of a CO_2 source (e.g. Trupp et al. 2013; Langford, 2016; Tanaka et al. 2017).

The results from one project-based investigation or outcome from decision-gate step may advance a site by more than one SRL. In some cases, new data could result in a lowering of capacity estimates. Such occurrences are to be expected with increased assurance of a site at higher SRLs. If the assured capacity or injectivity is deemed insufficient for a given CCS project the site would remain at the SRL attained until or when needed for another CO_2 storage project. The storage site appraisal remains available for a future project and assigned as 'development on hold' using the terminology of the industry project development classification SPE-SRMS (2017). Similarly, a potential storage site may remain at the SRL achieved within the national portfolio until a realistic full-chain CCUS concept is developed. It is also possible for a site to be taken out of the SRL framework completely if the analysis of new data concludes the site is not suitable for CO_2 storage.

3.12 Consistency with commercial project development classification

The framework of SRLs was designed to be consistent with and to extend the hydrocarbon industry SRMS commercial project development classification (SPE-SRMS, 2017). Where the SRMS classification categories are directly equivalent the same terminology was used to ensure consistency of use. The equivalence of the SRLs with the classification categories of the SRMS is illustrated in Table 3. The qualitative nature of the SRLs assessment, associated with a site's history of investigation and accrual of knowledge and the degree of judgement needed, is depicted as gradational boundaries between SRLs in Table 3. The SRL framework levels SRL 1 to SRL 4 assess prospective sites where the maturity of understanding is insufficient to be recognised as a 'storage resource' of the SRMS. The lower levels in the SRL schema categorise the many options and sites with insufficient data or lack of evaluation that occupy a position beneath the lowest SRMS class 'undiscovered storage resource'. The SRL framework can be applied to a concept for storage without the decision-making process assessing the commerciality of a CO_2 storage project of the hydrocarbon industry SRMS. However, linking the SRLs and SRMS categories, e.g. contingent storage resource, provides clarity on maturity of understanding to national decision makers and commercial storage operators rather than using undefined terms, such as bankable storage capacity.

Table 3 Equivalence of the SRLs framework with the SRMS (SPE-SRMS, 2017) project maturity classes and subclasses

<table>
<tr><th>Storage Readiness Level (SRL)</th><th colspan="3">Storage Resources Management System
Storage project maturity classes and subclasses (SPE-SRMS, 2017)</th></tr>
<tr><td>SRL 9 – Storage site on injection</td><td rowspan="6">Discovered storage resources</td><td rowspan="3">Commercial (capacity)</td><td>On injection</td></tr>
<tr><td>SRL 8 – Commissioning of the storage site and test injection in an operational environment</td><td>Approved for development</td></tr>
<tr><td rowspan="2">SRL 7 – Storage site is permit ready or permitted</td><td>Justified for development</td></tr>
<tr><td rowspan="3">Sub-commercial (contingent storage resources)</td><td>Development pending – Project activities ongoing</td></tr>
<tr><td rowspan="2">SRL 6 – Storage site integrated into a feasible CCS project concept or a portfolio of sites (contingent storage resource)</td><td>Development on hold or unclarified</td></tr>
<tr><td>Development not viable</td></tr>
<tr><td rowspan="2">SRL 5 – Storage site validated by detailed analyses, then a relevant ‘real world’ setting</td><td colspan="2" rowspan="3">Undiscovered storage resources</td><td>Prospect – Project sufficiently well-defined to be viable drilling target</td></tr>
<tr><td>Lead – Project poorly defined and needs data and/or evaluation</td></tr>
<tr><td>SRL 4 – Storage site validated by desktop studies and storage project concept updated</td><td>Play – Requires more data and/or evaluation</td></tr>
<tr><td>SRL 3 – Screening study to identify an individual storage site and an initial project concept</td><td colspan="3"></td></tr>
<tr><td>SRL 2 – Site identified as theoretical capacity</td><td colspan="3"></td></tr>
<tr><td>SRL 1 – First-pass assessment of storage capacity at country-wide or basin scales</td><td colspan="3"></td></tr>
</table>

The framework of SRLs and the SRMS classification have clear and different remits. The SRLs framework communicates maturity of understanding, assessing those activities completed and those remaining for a storage site to become operational, while the SRMS is a commercial resource evaluation appraisal. However, consistency of the framework of SRLs to communicate the maturity of understanding of storage site technical appraisal, regulatory permitting and the SRMS classification to guide project planning has clear benefits. Equivalence of the SRMS classification, prepared by the hydrocarbon sector for commercial evaluation of project-based storage resources, with the SRLs framework communicates maturity of understanding of storage site development to stakeholders without detailed knowledge of the subsurface. At the higher storage readiness levels consistency of SRLs with the SRMS commercial appraisal categories underlines the increasing assurance of containment, capacity and injectivity that is required to inform investor decision-making for CCS project development.

4 Pathways to operational CO_2 storage site

To illustrate the possible paths taken in the phased development of a storage site the standardised SRL framework (Table 1, Figure 1) was applied to the stages of investigation of three sites that were at a high SRL in 2020. A storage site was selected from each of the national CO_2 storage portfolios of the UK, Norway and The Netherlands that has been investigated as a component of a CO_2 storage project. The progress toward site operation was measured by the SRL achieved by each of the phased investigations and an indication, from publicly available sources, of the resources invested. The pathway of progress for each of the three sites with SRL at each phase of investigation is illustrated in Figure 3, Figure 4 and Figure 5: UK Endurance structure, White Rose Project; Norwegian Snøhvit CO_2 storage site; The Netherlands P18-4 Field for the ROAD Project. At the end of each project or phase of investigation a site may have advanced by several levels in the SRL framework.

4.1 White Rose Project, UK, storage appraisal pathway

The Endurance structure site (previously 5/42 of National Grid, 2016a) investigated for geological storage of CO_2 captured by the White Rose Project, Teesside, is a structural closure within the Bunter Sandstone saline aquifer formation offshore eastern England.

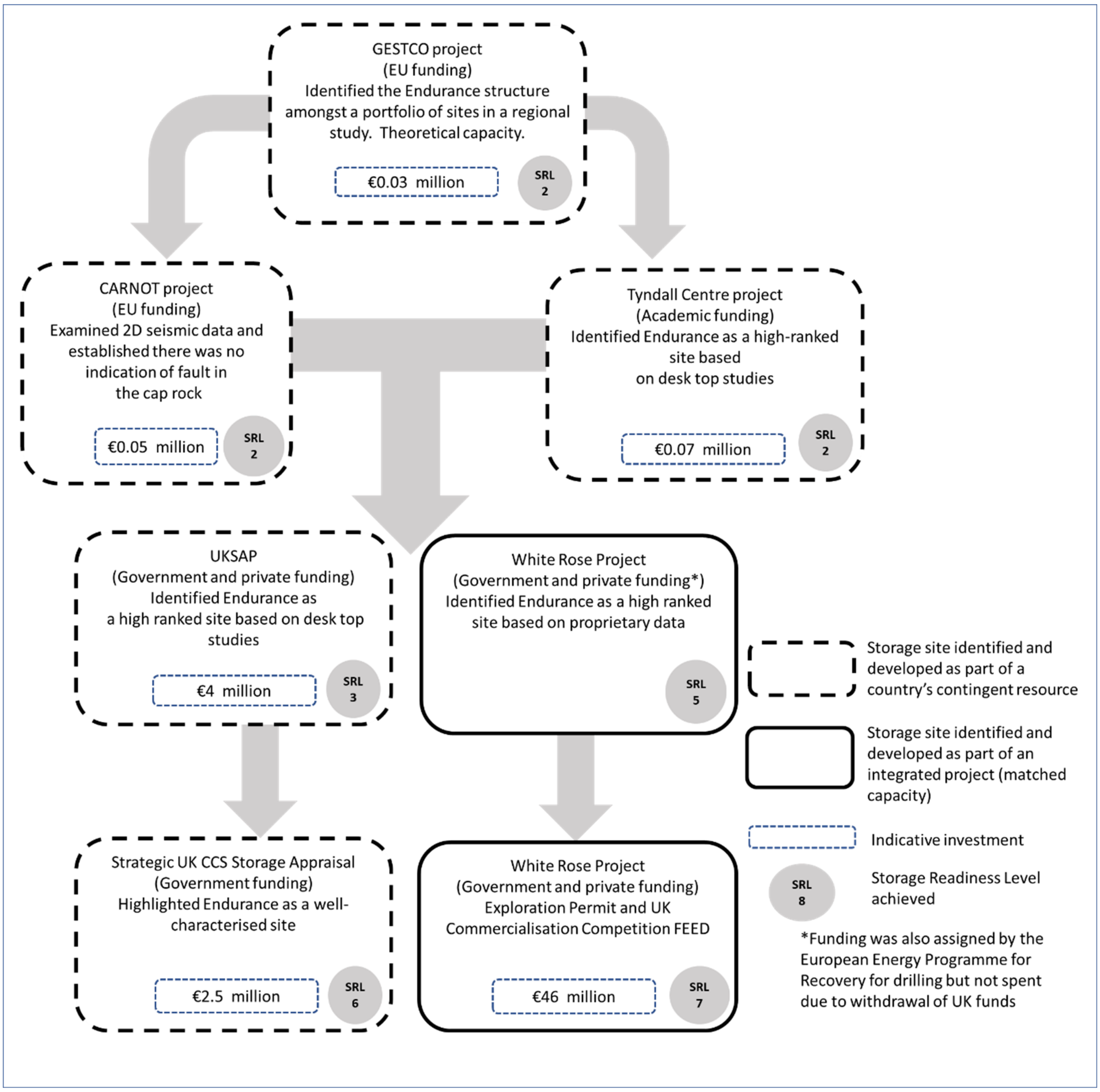

Figure 3. The SRLs achieved by project-based investigations of the UK White Rose project storage site (Endurance structure) illustrating pathways taken through the SRL framework. The sources of funding and the indicative level of investment are indicated for each phase of investigation in million Euro.

The appraisal pathway (Figure 3) distinguishes investigations of the national storage resource from planning of a CO_2 storage project. The sandstone was assessed as having substantial potential CO_2 storage capacity by Holloway et al. (1996) with mapping of theoretical capacity in structural closures during a regional storage capacity assessment at SRL 2 (Christensen and Holloway, 2004). Two concurrent studies, technical containment (Brook et al., 2004) and storage for power generation scenarios (Gough et al., 2006), widened the breadth of understanding of the theoretical capacity at SRL 2. Subsequently, investigations continued along two parallel pathways, each with more substantial funding. Understanding of the strategic UK national storage resource was increased to SRL 3 (Gammer et al., 2011; Bentham et al., 2014) and then SRL 6 (Pale Blue Dot, 2016). The UK national contingent resource assessment was supported mostly by government funding. Industry and government supported integration of the site as matched capacity for the White Rose Project (National Grid, 2016b) at SRL 5 and subsequently as a FEED project and permit ready at SRL 7.

4.2 Snøhvit site, Norway, storage appraisal pathway

The operating Norwegian Snøhvit CO_2 injection site was developed as an integrated component of a hydrocarbon production project (Hermanrud et al. 2013). The concentrations of CO_2 in the gas condensate produced are too high for sales gas and was required to be separated and stored. The operator had immediate access to seismic surveys and core samples and well logs from exploration wells. The pathway followed is that of a single hydrocarbon field development project with the progressive steps at SRLs 3, 5, 7 8 and 9 determined by investment decision gates (Figure 4).

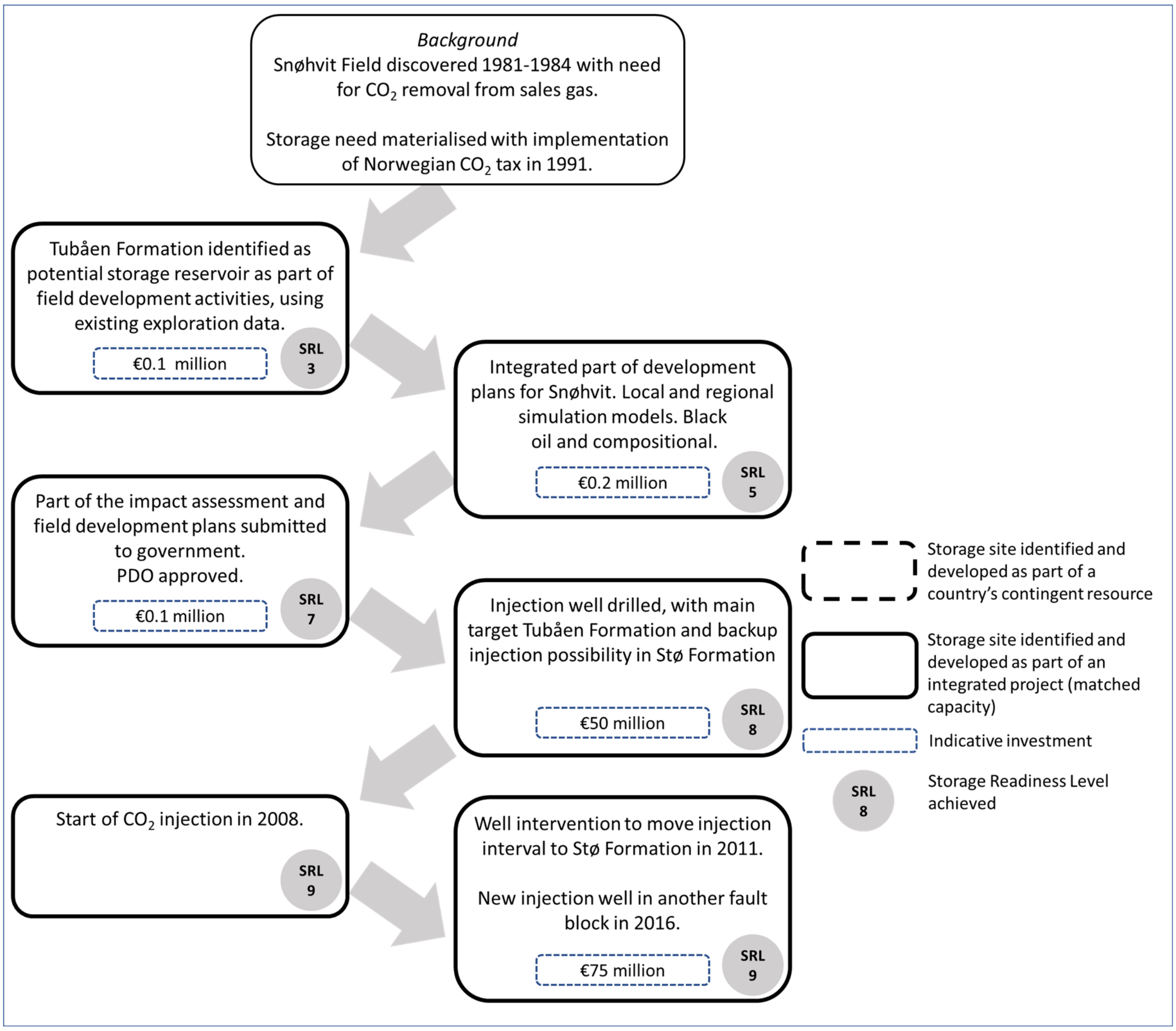

Figure 4. Pathway for the assessment of the Snøhvit CO_2 storage site project, Norway, and indicative investment by project development decision gate steps. PDO, Plan for Development and Operation of a petroleum deposit. Estimated investment costs, for SRL 8 and SRL 9 based on reported drilling rig times for the injection wells, in million Euro.

4.3 P18-4 Gas Field site, The Netherlands, storage appraisal pathway

The pathway for assessment of The Netherlands P18-4 site is a hydrocarbon field developed as a single project with two decision gate steps (Figure 5). The first assessment of the P18-4 field was undertaken in 2007, in a high-level estimate of CO_2 storage capacity that was made for the portfolio of onshore and offshore gas fields at SRL 2 and then capacity estimates based on publicly available reserves at SRL 3. The field was selected as the preferred storage site for the ROAD project and a storage feasibility assessment was carried out (Vandeweijer et al., 2011b). The conclusion that CO_2 could be safely injected and stored in the P18-4 field took the site to SRL 6 and an EIA was developed. A storage permit application was submitted in 2011 and the permit granted in 2013 at SRL 7.

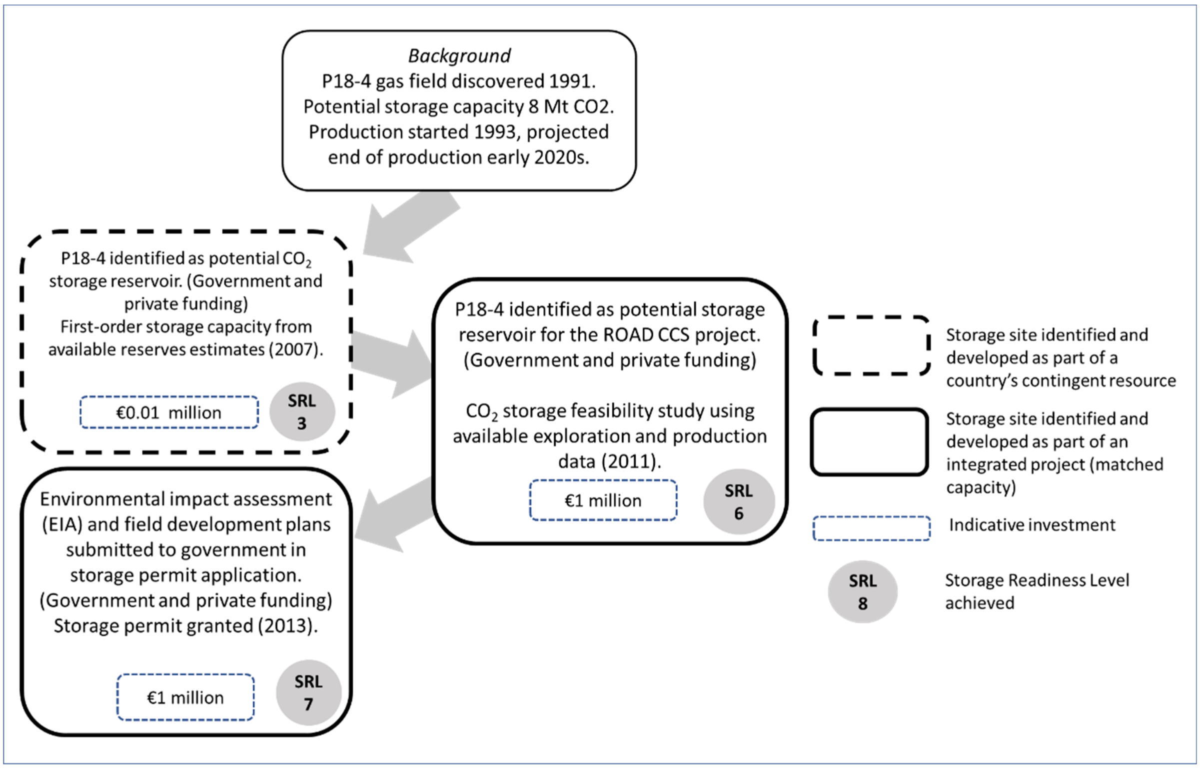

Figure 5. Pathway for the assessment of the P18-4 gas field storage site, The Netherlands, and indicative investment by project development phase. The sources of funding and the indicative level of investment are indicated for each phase of investigation in million Euro.

4.4 Learning from the pathways to operation

The SRLs framework was successfully applied to different store types, funding sources, strategic investigations, staged decisions or single straight-through projects, to benchmark and communicate progress to operational storage. Comparison of the three offshore storage sites, each in different national waters illustrates how each site has followed a different pathway. Advancement of maturity of understanding was determined by sequential storage resource projects in the UK (Figure 3) or investment decision gates within an industry-led CCS project in Norway (Figure 4). UK and The Netherlands pathways (Figure 3 and Figure 5) were initially advanced by research investigations undertaken by national bodies and subsequently public and private funding by industry-led projects confirming findings of Vincent et al. (2017). Advancement of a storage site beyond contingent storage resource at SRL 6 was supported by government and private funding of a CCS project in the UK and The Netherlands (Figure 3 and Figure 5). Each route is equally valid for the development and evaluation of a site for CO_2 storage and has been determined by the availability and timing of data and funding resources.

Communication of progress using SRLs is effective regardless of the scale of application. In the examples, this ranges from nationwide screening of aquifers and fields (SRL 2), and strategic appraisal (SRL 3) to industry site selection and project planning (SRL 7) as undertaken by the UK and The Netherlands examples Figure 3 and Figure 5). An even smaller, local scale is represented by the site screening and capacity assessment in the vicinity of a source (SRL 3) for the Norwegian Snøhvit Field, including identification of an alternative site at SRL 7 that was implemented at SRL 8. Should a site with proven matched capacity of the initial site be required it is already assessed to SRL 8.

The pathways to operation of the three sites all illustrate that individual investigations may advance the understanding, permitting and planning of a storage site by different routes. Benchmarking by application of the SRL framework communicates the increased maturity of understanding achieved by each investigation or investment. Concurrent investigations can take place where the objective differs (Figure 3). Parallel pathways may be taken for strategic investigation of the national storage portfolio and industry investment for investigation of a CCS project. Notably, investigations may not increase understanding appropriate for a higher SRL level if the objective does not address increased site understanding to assure permitting or inform project planning.

5 Indicative investment and duration for CO_2 storage site development

Application of the standardised SRL framework has enabled comparison of the permitting and planning activities specified within different jurisdictions, which differ in each nation although all have conformed to the same overarching guidance and regulatory requirements (EC, 2009, 2011). Application of the framework also allows identification of sites of equivalent SRL that have been planned or are operating in different jurisdictions. Learning gained from the European experience since the 1990s includes the level of investment and the duration to achieve equivalent SRLs for CO_2 storage projects. The experience of investment and timeframe for European offshore sites is compared with published estimates for onshore and offshore sites in Europe and the USA.

5.1 Methodology and results

Published and publicly available values and estimates of the cost and the timeframe for storage site appraisal and CCS project planning were reviewed for sites in the UK, Denmark, Norway, Italy and The Netherlands (references in Table 4). The SRL framework was applied to published assessments of other European storage sites and to a storage cost model for the USA (Grant et al., 2017).

Presentation of the costs (Table 4) by SRL is of necessity restricted to the level of detail within published and publicly available information. The published expenditure or estimated cost for technical appraisal, permitting and planning of a CO_2 storage site is presented for activities during site assessment (SRL 1 to SRL 3) site characterisation and design (SRL 4 to SRL 7), and construction (SRL 8) in Table 4.

The actual duration of technical appraisal to storage site permit application of three planned North Sea CCS projects in the UK and The Netherlands is summarised in Table 5. Estimates of the duration for appraisal and permitting by five assessments for CO_2 storage sites in the USA and UK, and by a European research project are also summarised in Table 5.

5.2 Indicative investment for storage site development

Estimates of required investment costs for storage site development still mostly rely on the analogy with development of hydrocarbon fields, though some examples exist of actual expenditure. Publicly available sources have been consulted to establish cost figures for expenditure or estimated costs for the main phases of development of a European storage site. Where sufficient details are available, cost figures are given for initial appraisal (SRL 1–3), characterisation and design (SRL 4–7) and construction (SRL 8). The cost figures provide a guide to the value of the financial commitment required before commencement of site operation (Table 4). However, it is important to note that the effort required to elevate the storage readiness of a site should additionally be measured by the data used and investigations completed to increase certainty for storage, rather than solely the cost expended.

Analysis of the available cost data shows that the level of investment needed will largely be dependent on:

- Site location, whether or not within a region of hydrocarbon exploration or production;
- Existing available data, such as well and geophysical survey data;
- Previously performed appraisals to achieve lower SRLs;
- Site type, whether a depleted hydrocarbon field or a saline aquifer site.

Table 4 Expenditure or estimated cost in million Euro (M€) for development of a European CO_2 storage site. Bold typeface on grey background incates actual expenditure, other costs are estimated, where available from public sources. Costs are split into separate values for appraisal (SRL 1–3), characterisation and design (SRL 4–7) and construction (SRL 8). Estimated costs for the final step to construction may not be available (NA) from public source. Estimated size of storage resource indicated in million tonnes (Mt).

	Country	Site	Type	Appraisal (M€) SRL 1–3	Characteri–sation and design (M€) SRL 4–7	Construc–tion (M€) SRL 8	CO_2 storage capacity (Mt)	Source of data
Expenditure	UK	Goldeneye Field	DHC	**3.2**	**48.8**	NA	30 – 36	Peterhead CCS FEED Project (Shell, 2016a, b, c)
Expenditure	UK	Endurance (Bunter Closure 35)	SA	**56.1**		NA	233* – 2600†	White Rose FEED Project (National Grid, 2016b)
Expenditure	UK	Hewett Field	DHC	**0**	**12.7**	NA	206	Kingsnorth FEED Project (E.ON, 2011)
Expenditure	Norway	Sleipner Field	SA	**1.6**	**< 2**	**10**	> 42	(Torp and Brown, 2005)
Expenditure	The Netherlands	P18-4 Field	DHC	**0**	**2**	36	8	(ROAD, 2018)
Expenditure	The Netherlands	Q16-Maas Field	DHC	**0**	**3**	55	2	(ROAD, 2018)
Estimated costs	UK	Hamilton Field	DHC	0	29.3	NA	125	S-SAP (Pale Blue Dot, 2016)
Estimated costs	UK	Bunter Closure 36	SA	63.4		NA	280	S-SAP (Pale Blue Dot, 2016)
Estimated costs	UK	Forties 5	SA	125.7		NA	300	S-SAP (Pale Blue Dot, 2016)
Estimated costs	UK	Captain X	SA	37.8		NA	60	S-SAP (Pale Blue Dot, 2016)
Estimated costs	UK	Viking A Field	DHC	0	34.2	NA	130	S-SAP (Pale Blue Dot, 2016)
Estimated costs	Denmark	Gassum Formation	SA	5	85	365	240	Skagerrak/Kattegat report (Bjørnsen et al., 2012)
Estimated costs	Denmark	Vedsted§	SA	10		6	60	SiteChar assessment (Gruson et al., 2015)
Estimated costs	UK	Outer Moray Firth (Blake Field)	DHC +SA	28		255	100	SiteChar assessment (Gruson et al., 2015)
Estimated costs	Italy	South Adriatic	SA	43		25	10	SiteChar assessment (Gruson et al., 2015)
Estimated costs	Norway	Trøndelag Platform	SA	81		30	40	SiteChar assessment (Gruson et al., 2015)

Storage types: DHC: Depleted hydrocarbon field, SA: Saline aquifer
* Theoretical storage capacity from the CO_2Stored database (www.co2stored.co.uk)
† Theoretical storage capacity from the White Rose FEED Project (National Grid, 2016b)
§ Onshore site

5.3 Timeframe for achievement of SRLs

The duration for technical appraisal of three planned sites through to SRL 7 and estimates of the duration for appraisal and permitting by five theoretical assessments are summarised in Table 5. The planned projects are two FEED studies funded through the UK Government, European and private funding and a FEED study supported by The Netherlands Government and private funding. The estimates of appraisal and permitting duration were supported by research and development funding from EU and/or UK Government funding or by governmental funding in the USA.

Estimated duration of technical appraisal and permitting

The S-SAP (Pale Blue Dot, 2016) and SiteChar (Gruson et al., 2015) projects estimated an appraisal and permitting duration of between two and three years based on existing data from potential storage sites. The estimates include the additional data that may need to be acquired and interpreted to increase certainty for a site's ability to retain CO_2. The estimated duration of the period needed to permit a site in Groenenberg et al. (2008) is four years. Their estimate is based on collation of details from operational and demonstration storage projects to provide a guide of the steps required and as part of licensing of a storage site (Groenenberg et al., 2008). The timescale provided in the UK government consultation to propose an appropriate licensing system for the geological storage of CO_2 from responses by industry and CO_2 experts (DECC, 2010) is five years for appraisal through to permitting. The longest duration of six years is estimated by the FE/NETL saline storage cost model of Grant et al. (2017).

Duration of technical appraisal and permitting for North Sea sites

The three North Sea FEED studies each provide a real timeframe for the appraisal carried out at the selected storage site. The UK appraisal of the White Rose saline aquifer storage site took 33 months. Not unexpectedly this was longer than the 20-month duration for appraisal and permitting of the hydrocarbon field site selected for the Peterhead CCS project. The pre-FEED work carried out for the Netherlands P18-4 depleted field provides an indication of the complete timeline, from storage feasibility study to permit approval. The duration includes the time taken by the European Commission regulator to issue its opinion.

The comparison in Table 5 illustrates that no set timeframe can be advised for site technical appraisal and permitting. The duration will be dependent on the type of site under investigation and the data that is already available for that site.

Table 5 Timeframe for appraisal stages and to storage permit application, also Storage Readiness Level at the start from previous assessments and at end of the assessment.

Site FEED study or theoretical assessment		Duration of appraisal	Total time to Storage Permitting (including appraisal)	SRL at start	SRL at end
Duration	White Rose FEED (National Grid, 2016a)	30 months	33 months	2	7
	Peterhead FEED (Shell, 2016a)	16 months	20 months	2/3	7
	P18-4 pre-FEED (ROAD, 2018)	24 months	48 months	2/3	7
Estimated duration	S-SAP (Pale Blue Dot, 2016)	3 years	3 years	2/3/4	8
	SiteChar (Gruson et al., 2015)	Minimum of 2 years	2 years	1	8
	CO_2ReMoVe (Groenenberg et al., 2008)	4 years	4 years	1	8
	Government Response to the Proposed Offshore licensing regime (DECC 2010)	4 years (depleted hydrocarbon field) 6 years (saline aquifer)	5 years	1	8
	FE/NETL Saline Storage Cost Model (Grant et al., 2017)	Minimum of 4 years (saline aquifer)	Minimum of 6 years (saline aquifer)	1	8

6 Conclusions

A framework of CO_2 Storage Readiness Levels is presented to communicate the progress of a site toward operational storage, for saline aquifer formations and depleted hydrocarbon field sites (Table 1). The overview of technical appraisal activities, CCS project permitting and planning likely to have been completed for each SRL (Figure 1) are based on three decades of experience of planning and operation of offshore North and Barents seas CO_2 storage sites. The SRLs are standardised by combining the national experience of appraisal, permitting and project development in the UK, Norway and The Netherlands. However, it is intended that the framework of SRLs should be more widely applicable.

The framework of SRLs provides a qualitative assessment of a site's readiness for operation and therefore its progress through the phased investment that culminates in storage project operation. SRLs are a qualitative appraisal and not a quantitative measure, since each site will have its own unique characteristics. There are no 'hard boundaries' between the levels and a degree of overlap of appraisal activities exists (Table 1). However, there are thresholds set by the regulatory permitting process which require completion of planning and, in turn, technical activities. The position of permitting thresholds will depend on relevant national legislation, even within Europe there are small differences in permitting requirements. The SRL indicates the level of understanding, permitting and planning achieved and so the progress toward operational CCS project at the time of the assessment. A site may achieve a higher SRL after subsequent technical investigations and project planning.

SRLs communicate the progress of a storage site toward operational storage to technical and non-technical stakeholders, whether industry project developers and operators or policymakers. They are consistent and complementary to published classifications of storage capacity, storage project development phases and methodologies and commercial feasibility (Table 3).

The SRLs framework enables assessment of all prospective sites from first-pass regional assessment at SRL 1, theoretical capacity at SRL 2, through contingent storage resource at full completion of SRL 6 and storage site operation at SRL 9. Advice from regulatory and industry stakeholders has ensured potential storage sites in a national storage portfolio and prospective sites for a CCS project at an advanced stage of planning can all be considered within the SRLs framework.

SRLs do not equate to the CCS Readiness Index of Consoli et al. (2017) which is a high-level analysis applied by country to rank major barriers and enablers for CCS deployment. The Global CCS Institute index (Consoli et al., 2017) quantifies national interest, policy, legal and regulatory frameworks and prospective storage resources by country.

Application of the SRLs framework to the national storage portfolios in the UK, The Netherlands and Norway illustrates offshore sites at all storage levels to SRL 7 for permit-ready or permitted sites in the three countries. The current and future progress of sites to operational storage will inform national strategies and planning to meet future emissions reduction targets. However, the SRL of sites may similarly be used to inform a regional approach spanning national boundaries. Application of SRLs can inform an assessment of the relative merits of CO_2 storage whether in sites at low SRLs within national borders or in sites at high SRLs in an adjacent or connected jurisdiction.

The pathway of appraisal of storage sites for the planned White Rose, UK, and ROAD, The Netherlands, CCS projects and the operational Snøhvit CO_2 storage site, Norway have been mapped to corresponding SRLs (Figure 3 to Figure 5). The results from a project-based investigation or outcome from decision-gate step may advance progression of a site by more than one SRL step. Each site has followed a different pathway through the SRLs framework determined by the availability and timing of data and funding resources, whether by sequential strategic resource projects or investment decision gates of an industry-led CCS project. Two of the pathways were initially advanced by research investigations undertaken by national bodies and subsequently public and private funding by industry-led projects. Advancement of a storage site beyond contingent storage resource at SRL 6 was funded by industry or by government and industry support.

The input of effort and resources required to attain each SRL step is not equal but concomitant to the level of detailed technical appraisal, permitting and project planning activities required to achieve them. Three regulatory stages provide thresholds for permitting of exploration at SRL 4, storage at SRL 7 and injection at SRL 8 (Figure 1). There are additional technical appraisal and project planning thresholds to confirm and assure the character of the storage strata and containing cap rock within SRL 5. Subsequently, completion of all iterations of risk-reduction technical analysis and appraisal work for the storage site mark the full completion of SRL 5.

The range of expenditure invested or cost estimated to achieve firstly SRL 3 and then up to SRL 7 or SRL 8 for sixteen storage sites in Europe provides a guide to the value of the financial commitment required before commencement of site operation (Table 4). Level of investment and timeframe are largely dependent on:

- Site location, whether or not within a region of hydrocarbon exploration and production;
- Existing available data, such as well and geophysical survey data;
- Previously performed appraisals to achieve lower SRLs;
- Site type, whether a depleted hydrocarbon field or a saline aquifer site.

Appraisal of a depleting field, with available data and extensively assessed during hydrocarbon production, is likely to require lower expenditure and be of shorter duration than for a saline aquifer storage site. Site exploration, assessment and development of a saline aquifer may be more costly and of longer duration than a hydrocarbon field store, although a saline aquifer site may be selected because of its larger capacity.

Research projects estimated durations of site appraisal and permitting are from 2 to 6 years. The experience of planned projects from three North Sea FEED studies is, in practise, that the duration of appraisal and permitting is somewhat shorter, taking between 20 and 48 months (<2 and 4 years) (Table 5). These first sites have tested the procedures for storage site permitting and the duration can quite reasonably be expected to decrease as the process becomes more familiar to both applicants and the regulatory authorities. Planning of the operation of a third or fourth site in the same formation as existing storage operations may allow more rapid or immediate progress through the SRLs owing to the familiarity of operations and permit application.

The definition of activities likely to have been completed for each level within the SRLs framework is based on characterisation and appraisal of offshore sites. However, application of the framework to 16 sites to enable comparison in different jurisdictions (Table 4) included an onshore site in Denmark and was equally readily achieved. In principle, the communication of the technical appraisal, planning and permitting by application of the SRLs framework should be the same for onshore and offshore sites. Although there may be different regulatory requirements, such as environmental assessments, and risk mitigation activities these are addressed by the national permitting requirements relevant to the jurisdiction.

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A Appendix A: Application of the SRLs framework to the national storage resource portfolios

Application of the SRLs framework (Figure 6) to the national storage resource portfolios of the UK, The Netherlands and Norway.

SRL number	Description/title of SRL	Indicative stage and assurance required for the site permitting process	Activities completed (indicative)
SRL 1	First-pass assessment of storage capacity at country-wide or basin scales	Site identified in national or regional reports on storage potential	Public data geological maps, published data and expert elicitation collated and reviewed . Area identified as having regional storage potential, e.g. by sedimentary basin
SRL 2	Site identified as theoretical capacity	Site included in a national or regional storage atlas. Theoretical storage capacity known and possible high-level containment concerns identified	Basic evaluation and volumetric calculation completed using publically available seismic data, well data, geological maps and published data
SRL 3	Screening study to identify an individual storage site & an initial storage project concept	Working toward or activities relevant to an exploration permit for a feasible storage site/project based on publicly available data	All readily available site-specific data accessed and compiled. Any major storage risks identified and data gaps highlighted
SRL 4	Storage site validated by desktop studies & storage project concept updated	Sufficient data to assure a potentially feasible store and/or project for achievement of an exploration permit	Initial modelling undertaken as proof of concept (regional and basic site-specific models), existing public data, e.g. well and geophysical data, and private data may be included,.
SRL 5	Storage site validated, firstly by detailed analyses, then in a relevant 'real world' setting	Investigation of existing data, acquisition and interpretation of new data sufficient to assure containment, injection rate and so CO_2 storage capacity as required to inform a storage permit	5a Detailed technical analyses and modelling completed, e.g. lab experiments, geochemistry & geomechanical stability, reservoir simulation and sensitivity analysis and field studies, as and if needed. 5b Direct evidence from new data collection, analyses and interpretation completed, e.g. confirmation well, well test and seismic survey data, as needed. Acquisition of data for EIA ♣, as and when needed. 5c All technical analyses of existing and new data completed
SRL 6	Storage site integrated into a feasible CCS project concept or portfolio of sites (contingent storage resource)	Final definition of the storage site within a project concept and FEED*	Comprehensive project risk assessment, risk reduction, risk mitigation activities and EIA ♣ completed
SRL 7	Storage site is permit ready or permitted	Storage permit acquired (or relevant equivalent ◆) or permit application ready	Preparation of storage site and project descriptions and plans: preventative measures, monitoring, corrective measures and site closure plans. EIA ♣ reported.
SRL 8	Commissioning of the storage site and test injection in an operational environment	Storage permit (or relevant equivalent ◆) revised, CO_2 injection permit application prepared and submitted.	Practical plans and construction of site completed. Containment and capacity confirmed by injection tests. Storage site plans revised for operational injection.
SRL 9	Storage site on injection	Site monitoring to meet regulators requirements	Model calibration, monitoring as planned, monitoring conformance reported to the Competent Authorities

◆ Equivalent of storage permit relevant to national jurisdiction. ♣EIA, Environmental Impact Assessment.

Figure 6. SRL number and title, indicative stage and assurance required for site permitting (brown) and an indication of the technical appraisal and planning activities that will or may have been completed (green) for each level.

A.1 SRL of sites in the UK national CO_2 storage portfolio

The framework of SRLs for sites is applied to the current level of understanding, permitting and planning for sites in the UK national CO_2 storage portfolio at the time of this assessment. The assessment is made on publicly available documents. The UK storage portfolio includes sites at all levels from SRL 2 to SRL 7. Sites at SRL 5 or above may have been investigated by more than one study or project and are described for the highest SRL achieved.

SRL 2 – Sites identified in a national storage database and theoretical capacity calculated

The UK has assessed the potential storage capacity within offshore sedimentary basins on the UK continental shelf. Potential storage sites have been identified in all the offshore basins assessed, Research projects and a UK strategic assessment investigated and identified sites and calculated the theoretical CO_2 storage capacity of UK offshore sites (Christensen and Holloway, 2004; Vangkilde-Pedersen et al., 2009; Bentham et al., 2014). All of the 570 prospective storage sites in the UK national CO_2Stored database, are at SRL 2 or above.

SRL 3 – UK screening studies identify individual sites and initial storage project concepts

Industry hydrocarbon operators have considered and identified re-use of suitable UK fields for CO_2 storage since the mid-2010s. Where assessed, the degree of existing understanding of fields by the operator places these prospective sites at an SRL higher than SRL 3. National (Gammer et al., 2011; Bentham et al., 2014) and regional screening studies (SCCS, 2011; Jin et al., 2012), supported by government and private funding, have identified and investigated illustrative *individual* storage sites and the regional capacity of the Captain Sandstone as a prospective storage formation at SRL 3. Risk information assessed includes geological information on faulting in the storage unit, on the cap rock, on compartmentalisation of the storage unit, and on the likelihood of formation damage.

SRL 4 – Regional UK assessment of aquifer storage sites validated by desktop studies

Detailed case studies from UK-wide appraisal have investigated two exemplars of saline aquifer storage sites, the Forties and Bunter Sandstones (Gammer et al., 2011). Flow simulations of CO_2 injection were performed and the impact of geological features such as top-surface structure, heterogeneity and differing boundary conditions were investigated by modelling storage security and CO_2 plume development up to 1000 years post injection. Generic and detailed models generated for these exemplar storage units improved calculation of static capacities using dynamic effects particular to each of the units chosen. These activities raise the level of understanding to SRL 4.

SRL 5 – Three UK storage sites validated by detailed analysis by research projects

Detailed site-specific risk assessment-led investigations supported by government, industry and research funding have raised understanding of three feasible storage concepts to within SRL 5.

Investigations were completed within the context of regional storage concepts within the Captain Sandstone; the SiteChar project investigation of the Blake Field (Delprat-Jannaud et al., 2015) and CO_2MultiStore project operation of two sites in the Captain Sandstone Fairway (SCCS, 2015).

Risk reduction-led investigation of storage in the Blake Field by geological modelling, dynamic simulation of CO_2 injection and coupled geomechanical modelling, regional migration pathway analysis and wellbore integrity modelling (Akhurst et al., 2015) was undertaken to inform a storage permit application. Whereas risk assessment-led research specifically investigated secure subsurface containment of CO_2 during simultaneous injection into two sites, the Goldeneye Field and a second saline aquifer site in the Captain Sandstone 40 kilometres to the west (SCCS, 2015). Both research investigations used site-specific data and conducted a single iteration of risk reduction appraisal, insufficient to reduce risk to an acceptable level, and no new 'real world' data was collected to further reduce the risks identified. The site investigated by the SiteChar research project (Akhurst et al., 2015) and CO_2MultiStore research project (SCCS, 2015) are at SRL 5a.

SRL 6 – Six UK sites assessed as contingent storage resource for feasible CO_2 storage projects

Six UK sites are assessed as contingent storage resource from two industry-led feasibility studies of CO_2 storage projects, five sites by Pale Blue Dot (2016) and one site by BP (2005). Five sites were progressed towards Final Investment Decision readiness by Pale Blue Dot, (2016): Hamilton Gas Field; Captain X Sandstone site; Forties Sandstone 5; Bunter Closure 36; Viking A Gas Field. All five sites investigated by Pale Blue Dot (2016) have site development plans including site characterisation, offshore infrastructure assessment, risk assessment, budget plan, injection strategy, transport strategy, monitoring, remediation and Competent Authority handover plans and are within SRL 6. The sixth site is the Miller Field (BP, 2005) investigated by an industry consortium that proposed the development of a demonstration project for commercial deployment by generation of hydrogen from natural gas. Storage of the produced CO_2 in the Miller Oil Field was to be used to enhance oil recovery. Existing pipeline and platform infrastructure was to be re-used, however, support for the project was not obtained. Although the wells and platform were later abandoned the pipelines have been left in place for potential future use for a CO_2 storage project placing the Miller Field site at SRL 6.

SRL 7 – Four UK permit-ready or permitted sites

FEED studies have been undertaken (Table 4) that have brought four sites to SRL 7. The appraisal and planning completed for the UK FEED projects (Shell, 2016a, b, c; National Grid, 2016b; E.ON, 2011) is sufficient for three storage sites – Hewett and Goldeneye fields and Endurance structure – to be deemed permit-ready. The Acorn Project has been awarded a storage permit for a portion of the Captain Sandstone (Crown Estate Scotland, 2018). This places all four sites at SRL 7.

A.2 SRL of sites in the Norwegian national CO_2 storage portfolio

Potential CO_2 storage sites on the Norwegian Continental Shelf have been studied in numerous research projects, e.g. Holloway (1996) and Bøe et al. (2002). The Norwegian storage portfolio includes sites at SRL 1 to 4, 6 and 7, and operational at SRL 9.

SRL 1 and 2 – Norwegian basins evaluated for CO_2 storage and sites identified in a national atlas

All sedimentary basins offshore Norway have been evaluated to SRL 1 by a first-pass assessment of storage capacity at basin scale. The theoretical storage capacities for both aquifer formations and hydrocarbon fields were assessed in the Joule II and GESTCO projects (Holloway et al., 1996; Bøe et al., 2002). Prospective sites in aquifer formations are at SRL 2 and identified as theoretical capacity in the Norwegian Petroleum Directorate storage atlas (Norwegian Petroleum Directorate, 2014).

SRL 3 – Screening studies identify individual sites and initial storage project concepts

Screening studies have identified individual storage sites and an initial project concept as candidates for either an extension to operating or planned full-scale CCS projects. A first assessment of storage feasibility, including appraisal of the cap rock, existing well data, injection rates, and CO_2 storage capacity has been undertaken for sites within the Utsira, Garn, and Sognefjord formations.

A shallow structural closure in the extensive Utsira Formation was selected as a storage site for the Sleipner CO_2 injection project (see below at SRL 9). Other structural closures in the Utsira Formation had also been investigated as potential storage sites in a series of research projects with simulations of long-term behaviour of injected CO_2 (e.g., Bergmo et al., 2009).

The total potential CO_2 storage capacity in the Garn Formation saline aquifer on the Trøndelag Platform, offshore mid-Norway, and the capacity within individual structural closures was investigated as part of the NORDICCS project (Lothe et al.; 2014, Lothe et al., 2016). Sensitivity studies for various mechanisms for increased trapping (dissolution and residual trapping, structural trapping from sealing faults) were conducted.

The Sognefjord Formation saline aquifer east of the Troll Gas Field has been the subject of several studies. Firstly, by the Norwegian Petroleum Directorate in the process of preparing the 2011 version of the Storage Atlas. Subsequently, by Gassnova as part of the initial feasibility studies for a Norwegian CCS demonstration project (Gassnova, 2016).

SRL 4 – One storage site validated by desktop studies

The Johansen Formation in the area of the Troll Gas Field was assessed as the storage component of a future Norwegian CCS project by Gassnova in 2016. New 3D seismic survey data was acquired in 2010, there was a re-interpretation of the geological setting, petrographic study of core samples and well log data was interpreted (Sundal et al., 2016). Validation by these desktop studies places the Johansen Formation site in the Troll area at SRL 4.

SRL 5 – Norwegian storage sites that have achieved the first permitting milestones

No sites are currently at SRL 5.

SRL 6 and 7 – Three Norwegian storage sites for feasible CCS project concepts

Three Norwegian sites have achieved SRL 6 as contingent storage resource components of feasible CCS projects. Two are for CO_2 Enhanced Recovery operations at the Draugen and Heidrun oil fields. The third is the Smeaheia site as a possible storage site for the Norwegian full-chain CCS demonstration project.

The Smeaheia site was selected in 2016 as the most suitable among three candidate storage sites in a pre-feasibility study for a Norwegian full-scale CCS project (Gassnova, 2016). The studies of the Smeaheia area benefitted from existing data from older petroleum exploration wells in the area. In 2017 further concept studies were commissioned. New commercial 3D seismic data has been acquired over a larger part of the structure, although at present no new exploration wells have been drilled. The Smeaheia site is at SRL 6, as a component of a full-chain CCS project with a defined source and transportation solution.

Reservoir simulation studies were performed between 2005 and 2007 for potential CO_2-EOR development at the Draugen and Heidrun oil fields in the Norwegian Sea offshore mid-Norway *(*Berenblyum et al., 2007). The reservoir modelling studies, performed in part by independent research institutes, were accompanied by in-house studies on necessary infrastructure development and total project economy by the operators. The annual CO_2 injection rate assumed for these projects (2-2.5 Mt) was planned from capture at an onshore gas power plant at Tjeldbergodden and transport by pipeline to the Draugen and Heidrun fields.

SRL 9 – Two operational CO_2 storage projects offshore Norway

There are two CO_2 storage sites ‘on injection’ at SRL 9 on the Norwegian Continental Shelf, both are integrated components of gas field developments. Offshore separation of CO_2 produced with the gas and injection into a saline aquifer formation was included in the project development plans for the Sleipner and Snøhvit gas fields.

CO_2 from the Sleipner Field is injected into the overlying Utsira Formation. Permitting was completed in 1992 and CO_2 injection commenced in 1996 after additional characterisation and assessment; operation continues to date. The field development plan for the Snøhvit Field, including CO_2 separation and storage in the Tubåen Formation was approved in 2002 and injection commenced in 2008. In 2011 the injection well was plugged, owing to injectivity issues, and re-perforated in a shallower part of the injection well, within the Stø Formation.

A.3 SRL of sites in The Netherlands national CO_2 storage portfolio

In The Netherlands the main focus of CO_2 storage development planning is on offshore depleted gas fields (EBN Gasunie, 2017), although offshore saline formations have also been considered. The Netherlands has storage sites at all levels of readiness from SRL 2 to SRL 7. The decision to invest in a CCS project firstly to commission and then operate a storage site has not yet been made in The Netherlands so there are currently no sites at either SRL 8 or SRL 9, respectively.

SRL 1 and 2 – All gas fields in The Netherlands identified as potential storage sites

All gas fields in The Netherlands, both onshore and offshore, are at SRL 2 as they have been assessed for CO_2 storage and their theoretical storage capacity estimated.

First-order CO_2 storage capacity estimates within hydrocarbon field sites in The Netherlands are based on Gas Initially In Place (GIIP) data. The gas field capacity estimates are included in the Geocapacity (Vangkilde-Pedersen et al., 2009) and CO_2Stop (Poulsen et al., 2015) databases to achieve SRL 2.

SRL 3 – Screening studies identify individual sites in offshore fields and aquifer formations

Screening for storage feasibility has been undertaken for offshore gas fields and aquifers, and offshore gas field clusters (Neele et al., 2012) to raise the selected Netherlands sites to SRL 3. Gas fields in the offshore P and Q blocks, offshore aquifers and gas field clusters K14/K15, K04/K05, K07/K08/K10, and L10/K12, have undergone first appraisal of feasibility for CO_2 storage. Cap rock, well data, estimated injection rates, storage capacity and availability for CO_2 storage have been assessed, raising the potential storage sites to SRL 3.

SRL 4 – The Netherlands Block Q1 aquifer and oil field storage sites validated by desktop studies

An initial risk assessment, based on publicly available data, completed for an aquifer formation and oil field sites in offshore block Q1 places them at SRL 4. The containment risks of the site's cap rock, well integrity, geomechanical modelling, and simulation of the behaviour of CO_2 in the reservoir have been assessed. A reference CO_2 supply rate was used rather than a project-related target rate or volume (Vandeweijer et al., 2011a).

SRL 5 – Detailed analyses of two gas field storage sites offshore The Netherlands

Two gas fields offshore The Netherlands have undergone sufficient detailed feasibility studies to achieve SRL 5. Detailed feasibility studies using all available data, including proprietary data, were completed for the Q08-A and P06-AB offshore gas fields (Hofstee et al., 2008; Pluymaekers et al., 2010). A reference CO_2 supply rate was used, as appropriate for assessment of a national portfolio of sites and a preliminary field development plan was formulated to achieve SRL 5.

SRL 6 – One gas field site for The Netherlands contingent storage resource

One gas field storage site comprises the contingent storage resource for The Netherlands. This field, Q16-Maas, was considered for storing the CO_2 captured at a Maasvlakte fossil-fuel power generation plant in the Rotterdam Port area, after downsizing of the ROAD project (Rotterdam opslag en afvang demonstratie project, one of the EEPR flagship CCS projects). The Q16-Maas field, located close to shore with a storage capacity of 1-2 Mt of CO_2, was to replace the larger offshore depleted field P18-4. Most of the geotechnical preparations for a storage permit application were completed for the Q16-Maas Field. A flow assurance study was performed, using realistic, project-driven, CO_2 supply profiles (ROAD, 2018). However, the ROAD project was cancelled in 2017, before a storage permit application for the Q16-Maas field was filed.

SRL 7 – Permitted storage capacity for The Netherlands ROAD and Porthos projects

The cluster of three gas fields in the offshore P18 block are at SRL 7. A storage permit has been in place since 2013 for the P18-4 gas field as the original storage component of the ROAD project[1] for storage of CO_2 from a Maasvlakte fossil-fuel power generation plant, Rotterdam. Feasible injection profiles were defined, based on the capacity and injection rates for the ROAD project and the flexibility of the store is known (Vandeweijer et al., 2011b).

In 2018, the Porthos consortium adopted the P18 gas field cluster as the preferred storage location for CO_2 captured at industrial sites in the Rotterdam Port area. With the storage permit in place for the P18-4 gas field, two additional storage permit applications for the P18-2 and P18-6 gas fields are being prepared.

[1] The storage permit for the P18-4 gas field can be accessed at https://zoek.officielebekendmakingen.nl/stcrt-2013-21233.html (in Dutch).