CCUS SET-PLAN

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UNLOCKING EUROPEAN CO_2 STORAGE CAPACITY: RECOMMENDATIONS ON THE STEPS REQUIRED TO DELIVER TARGET 7 OF THE SET PLAN'S IMPLEMENTATION WORKING GROUP ON CS AND CCU (IWG9)

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UNLOCKING EUROPEAN CO_2 STORAGE CAPACITY

Summary

The Implementation Working Group (IWG9) on Carbon capture and Storage (CCS) and Carbon Capture and Utilisation (CCU), a working group of the European Strategic Energy Technologies Plan have set a target to unlock European CO_2 Storage Capacity. This target requires at least 15 CO_2 storage sites by 2030 in preparation or operating in different settings and recognises the need to urgently appraise the geological sites that will be needed as CO_2 capture increases across Europe. Much progress has already been made in characterising the potential geological CO_2 storage sites for several projects, particularly in north west Europe and these appraisal initiatives are briefly summarised in this report. However, in order to support a number of decarbonisation pathways for energy-intensive and manufacturing industries, plus enable future options for decarbonisation of spatial heating via hydrogen use, significantly more storage capacity will be needed across Europe.

This report summarises the conclusions of the IWG9's Storage Subgroup, which comprises representatives from commercial storage developers, national geological surveys and storage regulators, and the research community. In 2016, the European Commission, the SET-Plan countries and industry agreed on 10 of ambitious targets for Action 9, outlined in a Declaration of Interest (DoI). In 2017, IWG9 elaborated the Implementation Plan of Action 9 that presents 8 Research and Innovation Activities to reach the DoI targets for 2020 and further actions to meet Key Performance Indicators for 2030. The IWG9 aims at involving more countries, more funders and more stakeholders in order to accelerate the large scale deployment of CCUS technologies and meet the targets of the Implementation Plan.

The IWG9 is composed of 11 SET-Plan countries (the Czech Republic, France, Germany, Hungary, Italy, Norway, the Netherlands, Turkey, Spain, Sweden and the UK), industrial stakeholders, non-governmental organisations and research institutions. The IWG9 has three chairs and its secretariat is ensured by CCSA, who is also the coordinator of the IMPACTS9 project, of which this report is a deliverable.

A number of priority actions have been identified and are described in this report:

Support 'pre-commercial' storage appraisal. The potential contributions that CCS can make to achieving Europe's Net Zero targets are predicated on the availability of sufficient geological storage capacity in the right locations and at the right times, and at appropriate economic costs. Determining the storage capacity available to meet these criteria requires careful geological appraisal at regional and national scales from which policies can be developed to enable CCS deployment at appropriate scales.

Determine where and how much storage appraisal is needed. This requires an understanding of likely future decarbonisation pathways. These policy choices will reflect potential rates of CO_2 capture from industrial decarbonisation, hydrogen production from methane reforming and the potential need for carbon dioxide reduction technologies such as bioenergy production with CCS and direct air capture with CCS.

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Collaborate on storage appraisal to increase speed, and reduce risks and costs. Storage capacity is available throughout all of Europe but it is located only in geologically favourable areas and is either held by oil and gas companies under permits or sits in open acreage with nobody responsible for its appraisal. Collaboration between countries will be needed to establish transport and storage networks that allow CO_2 to be transported across borders to suitable storage facilities. Collaboration in pre-commercial storage appraisal provides an early opportunity to establish and develop relationships between international parties (state and commercial), share costs and speed up assessment.

Oil companies should assess storage potential of their assets and fields. The oil and gas industry in Europe has taken positive early steps to investigate and appraise depleted gas fields for CO_2 storage. As other hydrocarbon fields reach the end of their economic production life, owners should be encouraged through regulatory and policy mechanisms to investigate their suitability for CO_2 storage development. Associated data and geological models should be made available for future storage developers to evaluate hydrocarbon bearing structures as well as aquifer and other structures. A European CO_2 storage atlas could make datasets available to prospective storage developers.

Test Injections should be undertaken in priority formations. Although the technical feasibility of CO_2 storage has been established for decades, injection tests in prospective formations with limited pre-existing data will create a positive basis for investments in capture projects and enable better and more robust estimates of wider storage capacity. In the absence of a mature market for CCS, unless a commercial entity steps forward, it is likely that public funding will be necessary to undertake these test injections.

Long-term and post-closure storage risks and liabilities should be addressed. Whilst there is now a global portfolio of industrial scale projects that fully demonstrate safe CO_2 storage, risks of leakage and induced seismicity remain a concern for the public. Therefore, the assessment and communication of technical risk and uncertainty should be a priority, that can be framed appropriately to address public concerns.

Although the technical feasibility of geological CO_2 storage has been proven in several projects worldwide, there remain opportunities to reduce costs and demonstrate the safety of CO_2 storage operations, through research and innovation. Cost reductions can be achieved by reducing risks and uncertainties, reducing development costs and reducing operational costs through a number of research priorities including lower cost drilling, oil and gas infrastructure reuse, and the development of tools to assess the occasional risks posed by legacy wells.

Lower developmental and operational costs, improved track record of safe operation and permanent storage and more efficient use of the pore space available can be achieved through research addressing the optimisation of trapping mechanisms at pore to reservoir scale, including validating the impacts of geological heterogeneity and trace components in the injected CO_2, on CO_2 plume migration and stabilisation.

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Demonstrating permanent containment will be essential to enable sites to operate with the support of both the public and regulators. Innovation in monitoring site performance can both improve the quality and fidelity of the data obtained and reduce costs of acquisition and interpretation. Priority areas for further research include real-time instrumentation, with new methods for automated interpretation. New technologies to detect and verify leakage, in the unlikely event it should occur, can reduce costs and improve detection, and accelerate repair.

Research should improve our understanding of processes occurring in the wellbore domain, as wellbore failures may lead to lower injectivity, migration or leakage. The impacts of trace components present within the CO_2 stream will be important considerations for assessing long-term wellbore integrity and phase behaviours. Field-scale experiments that enable improved understanding of leakage processes are a priority.

Finally, verifying, at field scales, predictions of processes that lead to enhanced containment of CO_2 within the deep overburden remains challenging. Deep borehole-based experiments that offer opportunities to understand containment processes should be supported.

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Introduction

In October 2020 the Implementation Working Group 9 of the Strategic Energy Technologies Plan agreed that the appraisal of CO_2 storage capacity was a fundamental step in the implementation of the Implementation Plan for CCS and CCU and therefore agreed to increase the ambition of Target 7: Unlocking CO_2 Storage Capacity. This was in recognition of the urgent need to appraise the geological sites that will be needed as CO_2 capture increases across Europe. Much progress has already been made in characterising the potential geological CO_2 storage sites for several projects, particularly in north west Europe. However, in order to support a number of decarbonisation pathways for energy-intensive and manufacturing industries, plus enable future options for decarbonisation of spatial heating via hydrogen use and achievement of carbon dioxide removal from the atmosphere through direct air capture and storage (DACCS) and bio-energy production with CCS (BECCS), significantly more storage capacity will be needed across Europe.

Target 7

Industrial decarbonisation of energy intensive industries and industrial processes such as cement, steel, plastics, chemicals and fertiliser production, requires the provision of sufficient deep geological storage capacity which must be available in the right locations and at the right time. This provides confidence that investments in CO_2 capture facilities by these industries will lead to reductions in CO_2 emissions and support their transition to low-carbon production.

Although dependent on the decarbonisation pathways chosen, reflecting a range of policy choices by countries, it is likely that in some countries significantly more storage capacity will also be needed to enable other decarbonisation technologies which may include:

- Fuel switching from natural gas to hydrogen. In the absence of large amounts of excess renewable electricity (for which vehicle electrification will also create significant demand) to enable large scale hydrogen production, increased hydrogen production can be achieved through the reforming of methane. Producing clean hydrogen via methane reforming requires permanent geological CO_2 storage at significant volumes. The hydrogen can be used to replace methane in industrial process, mainly heating, in power generation, in spatial heating and potentially to replace diesel in heavy goods vehicles and other large engine vehicles.
- Waste to power and waste to heat production can provide further benefits by capturing emitted CO_2. This can result in net negative emissions which is likely to be needed to offset emissions from other sectors, such as agriculture and land use changes, which are expected to be technologically and socially difficult to decarbonise.
- Carbon dioxide removal from the atmosphere through direct air capture and storage (DACCS) and bio-energy production with CCS (BECCS) can provide the necessary compensation or “headroom” for non-abatable GHG emissions in the effort to achieve climate neutrality.

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Storage appraisal activities will build on the prospecting opportunities identified in the European CO_2 Storage Atlas (ref. Target 5 of the SET plan´s IWG9).

Target 7: An interim target of at least 6 new CO_2 storage sites in preparation or operating in different settings (i.e. obtained or ready to submit an application for a storage permit). A target by 2030 of a further 9 sites to be appraised to the same level, in a range of geological settings, both onshore and offshore.

The SET Plan's Declaration of Intent states that, by 2030, 15 Permits for storage projects will be needed. This was based on an estimate of likely scale to reach commitments in the Paris Agreement (2DS). However, a further evaluation to get to Net Zero by 2050 is likely to require further increases in the number of storage appraisals after 2030. This will require the appraisal of storage sites in many regions of Europe beyond the current North Sea focus, and will include a need for smaller pilots, to accelerate wider CO_2 storage deployment. These smaller scale pilots should be included in southern, south-eastern, north-eastern and central Europe, in onshore locations.

The Target 7 is supported by Research and Innovation Activity 5: unlocking European Storage Capacity which is further described below.

Rationale for new target

Work has already been undertaken in the past to produce a European CO_2 storage database[1] that can facilitate the future development of CO_2 storage sites and further actions in this direction are expected in near future (see SET Plan IWG9 R&I activity 4 /target 5/, creation of a European CO_2 Storage Atlas) to be funded under the EC CSA call: "Support to the activities of the European Geological Services". Initial projects, planned under research and innovation activities 1 to 3, can be used to support the validation of the storage potential identified as part of R&I Activity 4. A number of storage appraisal projects are being undertaken in Denmark, Ireland, Netherlands, Norway, and the UK. However, in order to store the required quantities of CO_2 to attain targets under the Paris Agreement and to meet the European targets for net-zero emissions by 2050, new storage sites will need to be characterised and appraised every year for the next 30 years – raising their Storage Readiness Levels (SRL, see below). The storage atlas will identify potential storage locations to be evaluated. The Storage Resource Management System (SRMS[2]) provides an industry standard framework for reporting storage capacity estimates with clear levels of confidence and should be encouraged to be adopted by all appraisal projects. The SRL framework is complementary to the SRMS framework and support the maturation of storage sites towards industry investments.

[1] https://setis.ec.europa.eu/european-co2-storage-database The database and the associated visualisation tool was produced by the European Commission funded CO_2StoP project (CO_2 Storage Potential in Europe - Project No. ENER/C1/154-2011-SI2.611598). In this project, a first assessment of the European CO_2 storage capacity both onshore and offshore was made for all EU Member States and was completed in 2013. This analysis can be the starting point for an updated and comprehensive European CO_2 storage atlas- see R&I Target 4, which will be instrumental for the deployment of CCS in Europe.

[2] Storage Resource Management System published by the Society of Petroleum engineers, 2017.

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In parallel, all SET-Plan countries should establish national transport and storage plans and by aligning these national plans it will be possible to identify CO_2 storage projects that could be established as joint European CO_2 storage projects on the basis of their importance to European CCS development.

The principle of these appraisals is to prepare the way for subsequent larger scale activity. The appraisal may include assessing the storage capacity and containment of the formation and wider storage complex, and may include testing of injectivity to demonstrate storage technology/ies to the public as a safe and effective technology or to appraise the suitability of a storage location. The impact of these appraisals will be to increase the confidence of all stakeholders in CCS and the associated technologies. The first appraisal steps have started offshore in the North Sea, Irish and Celtic Sea regions. In later stages – building on the experience with offshore storage– storage can unfold onshore provided that the local public is supporting the safety and effectiveness of this mitigation technology. In this respect small-scale storage projects (pilots) can play a crucial role in visualizing the technology to the public.

Definition of storage readiness

CO_2 Storage Readiness Levels (SRLs) are a framework of technical appraisal, permitting and planning activities for the development of CO_2 storage sites (Akhurst et al., 2021). The framework is a communication tool to enable a common understanding of the technical appraisal of a storage site. SRLs convey the level of progress from an initial basic assessment of a prospective site to an operational store for a CO_2 storage project (Table 1). The framework of steps describes the activities required to achieve an operational site. SRLs are a qualitative description and not a quantitative measure of progress since each site is unique in terms of its technical and non-technical characteristics. The framework has been developed to inform technical and non-technical stakeholders' alike, whether prospective industry CO_2 storage project developers and operators, or policymakers developing a national storage resource portfolio. The framework enables assessment of all prospective sites from first-pass assessment at SRL 1, to contingent storage resource at completion of SRL 6 and storage site operation at SRL 9. Application of the SRL framework permits assessment of sites, whether for selection of a site by an operator in the proximity of a CO_2 capture project, strategic development of a national storage resource or government planning of CO_2 emissions reduction. Comparison of sites that have achieved the same SRL has also informed estimates of the range of expenditure invested and the time taken when planning and permitting of a CO_2 storage site. The framework is consistent and complementary with published capacity and commercial viability classifications. Consistent terminology, where appropriate, is used.

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Table 1: The Storage Readiness Levels Framework of Akhurst et al (2021).

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

Overview of existing and planned activities

Work has already been undertaken to produce a European CO_2 storage database and further work that can facilitate the future development of CO_2 storage sites is expected to be performed in near future (see R&I activity 4, creation of a European CO_2 Storage Atlas). Initial projects, planned under R&I activities 1 to 3, can be used to support the validation of the storage potential undertaken as part of R&I Activity 4. However, in order to store meaningful quantities of CO_2 to attain targets under the Paris Agreement, new storage sites will need to be characterised and appraised every year for the next 30 years. The storage atlas will help identification of potential storage locations to be evaluated. In parallel all SET-Plan countries should establish national transport and storage plans and by aligning these national plans it will be possible to identify CO_2 storage projects that could be established as joint European CO_2 storage projects on the basis of their importance to European CCS development.

Early activities fall into two categories;

- Pilots to demonstrate injectivity, demonstrate national capability and competence, improve public knowledge and support. The structure into which a pilot injection is being undertaken may have no large scale potential. Masses injected may be less than 100,00 tonnes and would therefore not require a storage permit.

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- Appraisal activity to map the extent, closure/seal, and injectivity. In this situation the structure will have large scale storage potential or confirm such potential for other nearby structures,

The benefit of a pilot is to demonstrate CO_2 storage technology/ies to the local/national stakeholders and the public as a safe and effective technology or to appraise the suitability of a storage location. The impact of a series of pilots will be to increase the confidence of all stakeholders in CCS and the associated technologies. In this respect small-scale storage projects will play a crucial role in visualizing the technology to the public, especially onshore and in countries where CCS still is an emerging technology. The PilotStrategy project will investigate geological CO_2 storage sites in five regions identified as promising for CCS. The consortium will focus on deep saline aquifers Detailed studies will be carried out on deep saline aquifers in the Paris Basin in France, the Lusitanian Basin in Portugal and the Ebro Basin in Spain. We will also develop our knowledge of CO_2 storage options in West Macedonia in Greece and Upper Silesia in Poland. Starting in June 2021 the project will run for three years.

To contribute to target 7, the new storage projects should confirm with the criteria listed below;

- Demonstration or evaluation of monitoring and verification techniques, and/or techniques for improving the storage performance (e.g. pressure management) for CO_2 storage or CO_2 EOR (onshore or offshore) as a temporary technology enabling the transition from a producing hydrocarbon field into a pure storage site
- Permeability, injectivity, pressure gradient and storage boundary tests by producing or injecting (not necessarily CO_2) fluid from or into target storage layers (onshore or offshore wells)
- CO_2 storage sites with cumulative injection of below 100,000 tCO_2. Such test injections do not require a storage license and will test technology to be applied elsewhere and/or investigate characteristics of specific subsurface layers (for example consider these pilots to be conducted onshore at relatively low cost to be extrapolated to large scale stores offshore)
- Where substantial investment (e.g. over 50 million €) is involved, it is recommended that the CO_2 storage pilot infrastructure should complement subsequent large-scale CO_2 storage onshore, which includes synergies with R&I Activities 1 to 4.
- Re-assurance of storage technology as a safe and effective climate mitigation measure in different onshore industrial settings by visualisation to local stakeholders and the public and their participative involvement.

Pathway to 2030 and beyond

In order to achieve the targets set out in the Declaration of Intent KPIs 15 Permits for storage projects need to have been granted or are in an advanced stage of permitting by 2030.These sites must provide sufficient storage capacity to enable rapid decarbonisation of industry and enable clean H2 production. Thereafter further storage capacity will be needed to enable BECCS and DACCS to be implemented as required. Test

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injections to prove capacity, as described above, will be needed to establish capacities in high priority formations where current knowledge is lacking. A process needs to be put in place by which information from small-scale storage projects may feed back into large-scale storage assessments and the European CO_2 Storage Atlas produced as part of actions under R&I Activity 4 of the Implementation Plan.

Horizon Europe, running until 2027 will fund research in CO_2 storage alongside other relevant aspects of the CCUS chain. The work programme includes support for CO_2 storage.

Accelerating CCS Technology (ACT) is a European initiative to establish CO_2 capture and storage as a tool to combat global warming. Currently, the initiative has ten funding partner countries in Europe. Its ambition is to fund research and innovation projects that can lead to safe and cost effective technology. From 2022, ACT is now expected to be incorporated into the new Clean Energy Transition Partnership, a multilateral and strategic partnership of national and regional RDI programmes in European Member States and Associated Countries with the aim to contribute to the implementation of the SET Plan.

Further development of CO_2 storage technologies to 2030 and beyond will require availability of world class R&D infrastructure. The ESFRI project ECCSEL was established in 2017 as a European Research Infrastructure Consortium (ERIC) and has an ambition to become a key R&D instrument to meet the objectives of the SET Plan. ECCSEL ERIC offers state-of-the-art R&D infrastructure related to CCS and aims at building and operating R&D infrastructure that can be accessed by researchers all over Europe, who are welcome to apply to use the infrastructure. The synergies between ECCSEL ERIC and ambitious R&D activities will be essential in developing safe and cost-effective solutions for CO_2 storage. ECCSEL ERIC will interact with relevant bodies, such as EERA, ETIP ZEP and others in order to ensure that ambitious R&D activities benefit from world class R&D infrastructure. ECCSEL ERIC aims to facilitate projects in the European Commission's Framework Programmes, future European industrial initiatives and education of specialists for the new CCS industry.

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Progress

The European Storage Directive (2009/31/EC) has been implemented in all member states, and has also been adopted in others such as Norway. Several of these countries, notably Denmark, France, Italy, the Netherlands, Norway and the UK, have fully implemented enabling legislation into national laws which encourage CCS development. Typically, this has involved a combination of new and/or adapting existing petroleum, mining and environmental legislation. Other European countries are encouraged to adopt a proactive approach where CCS is deemed to be needed to meet their climate mitigation goals.

Although implemented before the European Storage Directive regulations, long running projects such as the Norwegian Sleipner and Snohvit CO_2 storage projects, have successfully demonstrated the technical feasibility of CO_2 storage. They have now been shown to be fully compliant with the requirements of the storage directive as implemented in Norway.

The first joint European research on assessment of CO_2 storage potential was performed within the project '*The underground disposal of carbon dioxide*'[3] and was funded by the 3rd EU Framework Programme – *JOULE 2* action in 1993-1995. This provided the first estimates for European geological storage with theoretical storage capacities in the order of 800 billion tonnes with storage mainly located in the North Sea. These estimates were 'broad-brush' values, but nevertheless encouraging and thus lead to further work.

The Joule 2 project inspired the work carried out for the GESTCO project (from 2000 to 2003), a 3-year EU-FP5 project covering eight countries, Norway, Denmark, UK, Belgium, Netherlands, Germany, France and Greece. It was the first project to create a GIS-based map including CO_2 point sources along with potential geological storage site locations and capacities.

The *EU GeoCapacity* project ('*Assessing European capacity for geological storage of carbon dioxide*'[4]), has been the most comprehensive activity on mapping pan-European CO_2 storage potential so far. EU GeoCapacity (from 2006 to 2008) included data for 25 countries with comprehensive country reports, containing assessments of geological structures suitable for CO_2 geological storage, CO_2 point emission sources and infrastructure (pipeline) data. The main result was a GIS-based, pan-European database of CO_2 storage potential.

A specific targeted research project called *CO_2StoP* ('*CO_2 Storage Potential in Europe*'[5]) was funded by the European Commission in 2012-2013. Its aim was to establish a database of publicly available data for CO_2 storage potential in Europe. The project included data from 27 European countries, in most cases, using the public data from EU GeoCapacity. Only a few countries provided updates, based on developments funded at national level. CO_2StoP used an improved methodology for storage potential assessment, and a pan-European database has been produced. The database is owned by the EC Joint Research Centre in Petten,

[3] https://cordis.europa.eu/project/rcn/4997/factsheet/en
[4] www.geocapacity.eu
[5] https://ec.europa.eu/energy/en/studies/assessment-CO_2-storage-potential-europe-CO_2stop

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the Netherlands, and is available on the EuroGeoSurveys' European Geological Data Infrastructure (EGDI) platform.

According to the recent CO_2GeoNet report ´State-of-play on CO_2 geological storage in 32 European countries´[6], 25 countries reported updates of CO_2 storage capacity evaluation since the finalisation of the CO_2Stop database. The new European CO_2 storage atlas (ref. Target 5 of the CCUS SET Plan) shall include all these updates to provide an up-to-date inventory of European storage potential.

Since the first storage licence was awarded for the P18-4 depleted gas field in the Netherlands to Taqa, good progress has been made in appraising storage capacity, particularly in north west Europe, where appraisal has enabled a number of storage licences for exploration to be awarded. The third Implementation report on Implementation of Directive 2009/31/EC on the Geological Storage of Carbon Dioxide[7] covering the period 2016-2019 reported that three exploration permits have been awarded in the Netherlands (the Porthos project), in Norway (for the Northern Lights project) and in Andalucia, Spain. In the UK, five appraisal and storage licences have been awarded since 2012 (Table 2).

These storage exploration licences are linked to specific CO_2 capture transport and storage projects located in Netherlands, Norway and the UK. Other appraisal projects undertaken include:

The Greensand project, led by Ineos Energy, has undertaken an appraisal of the Paleocene sandstones of the Nini depleted gas fields in the Siri area of Denmark's North sea. This appraisal estimated that the storage potential is ½ million ton of CO_2 per year from 2025, increasing to 3.5-4 million tons of CO_2 per year by 2030.

The Cork CCS Project, now terminated, investigated the feasibility of CO_2 storage in the Kinsale Head Gas Field which has now ceased production. The study included evaluating to potential to reuse the gas field's infrastructure to store CO_2 captured from two gas-fired power stations and other industrial emitters in the Cork area of Ireland.

Table 2: *UK Exploration licences awarded since 2012.*

Licence Number	Applicant	Description
CS001	National Grid	To enable appraisal including drilling of a cored appraisal well, test injection and 3D seismic survey of the Endurance field, a saline aquifer structure in the Bunter Sandstone Formation, in the southern North Sea. The licence period has now terminated.

[6] http://www.co2geonet.com/media/73750/co2geonet_state-of-play-in-europe_2021.pdf
[7] https://www.eumonitor.eu/9353000/1/j4nvhdfcs8bljza_j9vvik7m1c3gyxp/vl37huhbo7vm

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CS002	Shell	To enable appraisal of the Goldeneye depleted gas field in the Outer Moray firth, within the Captain Sandstone formation.
CS003	Pale Blue Dot (Acorn)	To enable exploration and appraisal of the central North Sea Acorn storage site around the East Mey field.
CS004	ENI	To enable exploration and appraisal of storage options in the Liverpool bay area of the East Irish Sea, with appraisal of depleted gas fields within the region.
CS005(?)	Harbour Energy	Harbour's proposal is to reuse the Viking and Victor depleted Rotliegend gas fields, c140km from the Lincolnshire coast, and potentially utilise the Bunter Formation aquifer which could offer additional options to increase the future storage capacity of the project.

These projects have required the development of procedures to manage long-term liabilities between operators and regulatory authorities. There is therefore an opportunity to share this good practice with other countries to encourage the development of policies and regulations that have the benefit of being developed and tested previously. The sharing of this good practice between regulatory authorities would provide a good foundation for countries to implement CO_2 storage projects. In addition, approaches to managing cross-border CO_2 transport and storage are being developed which can provide exemplars of required regulatory approaches and business models that allow capture projects to utilise storage capacity developed internationally and therefore requiring the export of CO_2 as a waste product. Further work is required, however, to understand the implications on future obligations and liabilities associated with this cross-border transport and storage.

Nevertheless, despite the increase in appraisal activities described above, further storage must be appraised to ensure sufficient storage capacity is made available to meet future requirements from capture projects. Achieving this appraisal requires a number of actions that are summarised in the following sections.

As summarised above, to date most storage appraisal has been undertaken offshore in northwest Europe, mainly the North Sea, Irish Sea and Celtic Sea. Appraisal of promising storage locations must be increased to create a portfolio of storage options for industrial regions across Europe.

Although the Implementation Plan has set a target of achieving 15 storage permits by 2030, which covers a range of locations and storage options, and requires a significant increase in the rate of appraisal each year throughout the 2020s, the focus should not be on the number of permits but rather the provision of sufficient storage capacity to meet predicted capture rates. This requires identification of the most appropriate storage options through national atlases. Eventually this will also include using a European storage atlas[8] to identify

[8] See a companion report: Recommendations on the steps to establish a R&I Activity 4 European Storage Atlas available at CCUS SET-Plan

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those locations of strategic importance at regional level to facilitate the development of storage hubs which can lead to cost-effective scale up of storage. Furthermore, the identification of the most appropriate locations requires consideration of potential pathways (and the necessary policy development) to decarbonisation which will inform the likely range of storage capacities that may be needed for a given industrial cluster, country or European region. For example, a review by Butnar et al, 2020) indicated that for Europe as a whole to reach the 1.5 C target capture rates have been estimated to be between 230-430 $MtCO_2$/yr in 2030, increasing to 930-1200 $MtCO_2$/yr by 2050. However, there is considerable uncertainty and Butnar et al., (2020) found that CCS was not always fully represented in the models used to illustrate these scenarios. In addition, Butnar et al.'s review identified that in the 1.5°C scenarios, the median CO_2 captured by BECCS is 30 $MtCO_2$/yr in 2030, increasing to 400 $MtCO_2$/yr by 2050. Assuming simple linear increases in the rate of capture, these annual capture rates at industrial emitters would require a total storage capacity of approximately 12 to 17 Gt (12,180 to 17,115 Mt CO_2) to accommodate the CO_2 captured between 2030 and 2050. BECCS would require an additional 4.5 Gt of storage capacity. It is difficult to estimate the current 'licenced' storage capacity in Europe but an estimation, based on publicly available information, is that current licenced storage capacity is less than 2 Gt. Given the time taken to appraise a potential storage site, of up to 5 years, and the number of sites that may be deemed unsuitable for storage following their appraisal, we anticipate that up to 20 sites must be appraised at a rate of 1-2 per year to 2030 as we expect a number of site to be found unsuitable for storage following appraisal. The exact numbers of sites needed will, of course, depend on the storage capacities of each site, their locations and evolving policies in support of decarbonisation.

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Priority actions

The need for 'pre-commercial' storage appraisal

The potential contributions that CCS can make to the decarbonisation of energy-intensive industries and industries that produce CO_2 during their manufacturing processes, to establishing a hydrogen economy and to enabling greenhouse gas removal technologies are predicated on the availability of sufficient geological storage capacity in the right locations and at the right times, and at appropriate economic costs. Determining the storage capacity available to meet these criteria requires careful geological appraisal at regional and national scales from which policies can be developed to enable CCS deployment at appropriate scales. This regional and national assessment of storage potential is a necessary foundation before commercial CO_2 storage projects can be developed and all countries that are currently developing commercial-scale CCS projects have foreseen a need for a national storage appraisal which then supports commercial CCS project development anchored at specific storage sites. However, this regional and national appraisal is insufficient by itself to enable development of an individual store which requires significantly more detailed geological assessment.

Countries that are implementing CCS have now embarked on a separate programme of storage appraisal that is independent of specific capture projects. This appraisal is at various levels of development from "national" projects such as Project Longship to support for a range of site investigations linked with regional decarbonisation located within industrial clusters in the UK (ACORN, HyNet and the Northern endurance Partnership). In addition, in the Netherlands a number of projects are developing CCS infrastructure: the Porthos project is developing a pipeline for gathering CO_2 from multiple sources delivering to TAQA offshore P18-4 storage site by pipe and the Aramis hub will receive and export CO_2 via ship and pipe to Shell/Total. This allows some of the challenges and fragility of single linear CCS projects to be overcome and reflects the recognition that the T&S infrastructure must be in place to enable wider and deeper CO_2 capture to be implemented. It also provides the evidence of future storage availability to encourage investment and project development – especially for capture projects which need confidence that the storage capacity will be available when it is needed.

We encourage the EC to develop guidance on what Competent Authorities and Member States should do to develop a CO_2 transport and storage industry. Recent progress and approaches taken in leading countries such as the Netherlands, Norway and the UK should be shared and examined as models for such guidance. This could include, inter alia, mechanisms to encourage oil and gas licence holders to assess the potential for their fields to be used for CO_2 storage, collaboration between countries, enabling policies on transfer of ownership and associated liabilities from oil and gas licence holders to storage licence holders and improved regulations that reflect our current understanding of risks associated with different store types. These are further discussed below.

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Where and how much storage appraisal is needed?

In order to determine how much storage capacity might be needed, and when it will be needed, requires an understanding of likely future decarbonisation pathways and associated policy choices. These policy choices will reflect potential rates of CO_2 capture from industrial decarbonisation, hydrogen production from methane reforming and the need for carbon dioxide reduction (CDR) technologies such as future development of bioenergy production with CCS (BECCS) and direct air capture with CCS (DACCS). These choices are likely to vary between regions and between countries reflecting variations in economic activity, population characteristics and energy systems. The rates of BECCS and DACCS implementation will partly be determined by their benefits in offsetting emissions from other, harder to decarbonise sectors, as well as costs. DACCS and BECCS operations could be located close to storage locations to reduce transport costs, further increase safety, and maximise cost efficiency.

Providing a strategic oversight of where and how much storage capacity will be needed requires policymakers and their advisors to understand the potential rates of CCS in their region, which requires an understanding of the theoretical amount of storage capacity available. Whilst this has been achieved in many European countries, not all have a national understanding which is included in national policy development. Establishing future possible capture rates therefore enables the required storage capacities to be defined and when they will be needed.

Developing storage capacity, through appraisal, is considered a no-regrets action. Currently there is insufficient storage capacity readily available to achieve current targets and therefore increasing the readiness of additional storage capacity is likely to result in increased and earlier investments in decarbonisation from CO_2 capture, and other low-carbon and CDR options described above. Since appraising storage and securing storage permits can take many years, these activities must be initiated at least five years before CO_2 capture installation.

Developing onshore storage is a priority and would bring significant benefits including reducing costs relative to offshore storage. The drilling and construction of CO_2 storage facilities onshore is generally significantly cheaper than when undertaken in the offshore environment. The provision of onshore storage closer to emitters will also reduce the cost of transport options. Furthermore, in some cases smaller onshore storage options may provide opportunities for some emitters, that are located at sub-economic distances from the principal future transport and storage networks to implement CCS more quickly and at lower costs relative to other options. However, it has long been recognised that onshore storage requires supportive local communities to host the facilities and securing this support will require focussed and careful dialogue, including during site appraisal stages. Comparisons can be made with hydrocarbon bearing structures that have been stable, containing buoyant fluids for 100s million years. CO_2 storage could be considered as returning the carbon to where it came from, and potentially returning the original pressure underground to close to where it has always been before hydrocarbon production began. Demonstration of the technology to the national and local stakeholders and to the public by means of small-scale pilot projects can significantly

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contribute to its public support, especially in countries where CCS is still an emerging technology. In addition, onshore storage may incur additional land access costs.

Collaboration will increase speed, reduce risks and costs

Storage capacity is available throughout all of Europe but its locations are concentrated in geologically favourable areas. Not all countries and industrial regions or clusters, will have indigenous storage capacity. This therefore implies that collaboration between countries will be needed to establish transport and storage networks that allow CO_2 captured to be transported internationally across borders to suitable storage facilities. Collaboration in appraising storage, which may also cross borders, also brings benefits in terms of reducing individual county investment costs, speeding up the assessment and reduces the risks of investing by sharing risks between several parties. Collaboration in pre-commercial storage appraisal provides an early opportunity to establish and develop relationships between international parties (state and commercial).

In addition to collaboration on appraisal, in order to develop strategic storage resources, collaboration could include the alignment of policies and regulations. For example, the development of projects of common interest could facilitate the development of storage hubs for cross-border transport and storage of CO_2. Regulatory collaboration might require strategic management of a “shared” pore space to maximise efficient use of the pores space, manage pressure responses and facilitate the re-use of hydrocarbon assets, pipelines and shared infrastructure.

Furthermore, whilst a number of mechanisms exist for sharing knowledge between project developers, sharing knowledge between policy makers and regulators should also be encouraged to share good practice on a range of topics including managing the storage permitting process, capabilities and capacities required to manage storage permitting, and appropriate policies to support storage appraisal, development and operation. A particular challenge remains in understanding how long-term, post-injection liabilities for CO_2 can be appropriately managed across international boundaries. Again, significant progress has been made in this by projects such as the Project Longship in which potential CO_2 capture locations from across Scandinavia have developed agreements to store CO_2 in the Norwegian site.

Oil companies should assess storage potential of their assets and fields

The oil and gas industry in Europe has taken positive early steps to investigate and appraise depleted gas fields for CO_2 storage. Examples include the P18 gas fields for the Porthos project in the Netherlands, gas fields of the Central North Sea for the ACORN project in the UK, the gas fields of the Liverpool Bay area in the East Irish Sea for the Hynet project in the UK, the Kinsale gas field in the Celtic Sea for the Cork CCS project and the Nini fields in the Danish North Sea for project Greensand in Denmark. These projects across north west Europe demonstrate the feasibility of storing CO_2 in depleted gas fields, the advantages of which include proven traps, and accessible infrastructure leading to lower cost developments. As other hydrocarbon fields reach the end of their economic production life, owners should be encouraged through regulatory and policy mechanisms to investigate their suitability for storage development. This will lead to a portfolio of fields that

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can be prioritised through 'site selection' exercises to determine which should be converted to storage operations and which might be needed in the future, requiring mothballing and preservation.

Petroleum licences holders should publish plans on whether their licence area is suitable for CO_2 storage and these plans must be updated annually. Operators of sites independently identified (e.g. via a European storage atlas) that offer significant potential for storage should be required to relinquish their licences if they do not have plans for storage. Governments should develop policies that set clear routes for the transition from a producing hydrocarbon field to a CO_2 storage site and for the transfer of ownership from an oil and gas operator to a storage developer, with the associated transfer of liabilities for decommissioning clearly defined.

Potential "high-ranking" storage sites without incumbent licence holders, typically expected to be saline aquifer sites with no previous economic value, should be proactively promoted to encourage storage development. Exploration and appraisal of these structures is, as described above, require pre-commercial exploration as there is currently a lack of economic incentive for potential storage developers to undertake this exploration and development.

Furthermore, associated data and geological models, including production data and other related data such as reservoir pressure data, seismic exploration data, fluid chemistries, core materials, and analyses, and geological models, well log reports and high quality well completion and P&A reports should be made available for future storage developers. The mechanisms for preserving and publishing these important datasets varies between countries but typically involves national geological surveys, petroleum departments of government and regulatory agencies. A European CO_2 storage atlas could also serve this data management function, making available datasets to prospective storage developers.

Test Injections needed in new formations

In contrast to the early opportunities for storage provided by the reuse of hydrocarbon fields, especially depleted gas fields, there is generally significantly less direct observation and data acquisition available in saline aquifers, reflecting their lack of economic value. Although the technical feasibility of CO_2 storage has been established for decades, injection tests in prospective formations with limited pre-existing data will build confidence with all stakeholders. It will create a positive basis for investments in capture projects and enable better and more robust estimates of wider storage capacity. The purpose of these tests is to establish the injectivity (rate of injection and scale of connected pore volume that will be accessed or impacted during operation). Such tests injections have been undertaken in other CCS projects including Sleipner, Longship and the Endurance field, as well as projects internationally (notably in the Illinois Basin where the Decatur project established high quality storage potential via appraisal wells and injection tests which subsequently led to industrial scale CCS projects).

Test injections will also be particularly important onshore where the management of produced waters may also be a concern in some formations. Injection tests in highly prospective formations would form part of the

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storage appraisal, either at a pre-commercial stage or during initial commercial project development. Furthermore, test injection projects, which openly address the concerns of communities, will allow more rapid and lower-cost CCS deployment. Injection tests could also evaluate the potential of other additional benefits such as the potential for geothermal heat production where tests can evaluate the geothermal prospectivity of a target formation.

Long-term and post-closure storage risks and liabilities remain a concern for the public.

Long-term and post-closure risks of leakage and induced seismicity, as well as the impacts of natural seismicity, remain concerns for the public Whilst there is now a global portfolio of industrial scale projects that fully demonstrate safe CO_2 storage, further focus on the assessment and communication of technical risk and uncertainty should be a priority. This requires an understanding of leakage risk prediction and reduction that can be framed appropriately to address public concerns. The demonstration of robust conformance between observed behaviour and predictions of future behaviour to develop and communicate a robust CO_2 storage safety case throughout project lifecycle, and especially for closure and post-closure remains a high priority. Coordination amongst projects, regulators and policymakers should be supported to enable other regions to benefit from early developments in these areas.

Although the London protocol now permits transfer CO_2 between countries for the purpose of permanent geological storage, regulations are needed to support the development of projects to store CO_2 in another country. In particular, sharing of good practice between national regulatory authorities on development of appropriate liability sharing and associated transport business models is needed to support a growing international transport and storage industry. Sharing the approaches taken in the Projects of Common Interest, and of policies developed in some countries to support future liability transfer between countries and other projects should be encouraged.

There is also an opportunity to reduce costs by developing 'fit-for-purpose' monitoring regulations, that are flexible to take account of the different conditions and associated risks of different storage sites, and especially following site closure. The monitoring requirements in the post-closure period (after the end of injection), should be flexible to take account of the specific pressure regimes and containment processes. For example, storage in pressure-depleted gas fields may not require significantly reduced or no post-closure monitoring, where pressures have returned to less than hydrostatic pressures and therefore may offer lower cost solutions relative to conditions that could be found at the end of injection in saline aquifers, where pressures may be above hydrostatic pressures. Similarly, where geological structures are likely to prevent lateral migration and caprocks are very unlikely to allow permit any upwards migration, then post-closure monitoring may be able to be reduced. Storage targets, including depleted gas fields, below the Permian Zechstein evaporite of the Southern North Sea would be a prime example of these types of storage opportunities.

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Research priorities

Although the technical feasibility of geological CO_2 storage has been proven in several projects worldwide, there remain opportunities to reduce costs and improve the safety case of CO_2 storage operations, through research and innovation. Cost reductions can be achieved by reducing risks and uncertainties, reducing development costs and reducing operational costs through a number of research priorities including:

- Lower cost drilling – particularly at onshore locations
- Asset reuse. The Rex CO_2 project has developed innovative tools to help assess whether wells can be reused for CO_2 storage, including repurposing for monitoring wells and injection wells. Further opportunity exists to extend this innovation through testing and wider expansion.
- The risks posed by legacy wells remains a potential challenge in some storage locations and further research is needed to understand and develop tools to assess the credible risks posed by these legacy wells, including assessment in absence of high-quality abandonment records.

Research to understand in detail the processes that can enable improved safety and efficient use of the pore space available will lead to lower costs and more successful projects. Research priorities include

- Understanding and optimising trapping efficiencies. Much is already known of the different mechanisms that lead to permanent CO_2 storage but validation of these processes at scales relevant to commercial deployment are required. Addressing topics such as the impacts of heterogeneity on CO_2 plume migration and trapping at reservoir scale requires further investigation. Predictions of long-term CO_2 plume stabilisation processes should be verified through field tests at industrially relevant scales for a range of geological storage types, but especially in saline aquifers and where lateral migration of CO_2 is expected. Finally, the impacts of small concentrations of components derived from the capture processes, including expected combinations of these components, on the relative importance of trapping processes must be understood to ensure to ensure predictions of future containment are sufficiently accurate.
- Demonstrating permanent containment will be essential to enable sites to operate with the support of both the public and regulators. As summarised above this requires monitoring of the storage operation to establish the veracity of predictions of future site performance and the permanent containment that is a pre-requisite for storage. Innovation in this monitoring can both improve the quality and fidelity of the data obtained and potentially reduce costs of acquisition and interpretation. Priority areas for further research include
    - Real-time instrumentation and permanent and continuous monitoring, with new methods for automated (machine-learning) interpretation of data acquired.

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- Monitoring for leakage detection and verification has been a focus of research globally which has established the technical capabilities and requirements. New technologies can be applied to reduce the costs and improve the detection, in time and space, of leakage events should they occur, and of processes that might subsequently pose a risk of leakage.
- Understanding processes occurring in the wellbore domain at industrially relevant scales provides significant opportunities to improve our understanding of wellbore failures which may lead to lower injectivity, or leakage. The impacts of trace components present within the CO_2 stream will be important considerations for assessing long-term wellbore integrity and phase behaviours. Field-scale experiments that enable improved understanding of leakage processes are a priority.
- Verifying, at scale, predictions of processes that lead to enhanced containment of CO_2 within the deep overburden remains challenging. Deep borehole based experiments offer opportunities to understand the geochemical and geomechanical responses of the deep overburden in some leakage scenarios and these should be supported.

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