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SiteChar

Characterisation of European CO_2 storage

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1 Executive summary

The objective of SiteChar was to facilitate the implementation of CO_2 geological storage in Europe by developing a methodology for the assessment of potential storage sites and the preparation of storage permit applications. Research was conducted through a strong collaboration of experienced industrial and academic research partners aiming to advance a portfolio of sites to a (near-) completed feasibility stage, ready for detailed front-end engineering and design and produce practical guidelines for site characterisation.

SiteChar examined the entire site characterisation process, from the initial feasibility studies through to the final stage of application for a storage permit, on the basis of criteria defined by the relevant European legislation: storage capacities, modelling of aquifers at basin or reservoir scale, injection scenarios, risk assessment, development of the site monitoring plan, technical and economic analysis (*i.e.,* assessment of all the costs related to storage), public awareness, *etc*. The SiteChar workflow for CO_2 geological storage site characterisation provides a description of all elements of a site characterisation study, as well as guidance on these issues, to streamline the site characterisation process and make sure that the output covers the aspects mentioned in the EC Storage Directive. A key innovation was the development of internal 'dry-run' permit applications that were tested by relevant regulatory authorities. This process helped to refine the site characterisation workflow and aimed at identifying gaps in site-specific characterisation needed to secure storage permits under the EC Storage Directive, as implemented in 'host' Member States.

The research focused on five potential European storage sites, representative of the various geological contexts, as test sites for the research work: a North Sea offshore multi-storage site (hydrocarbon field and aquifer) in Scotland, an onshore aquifer in Denmark, an onshore gas field in Poland, an offshore aquifer in Norway and an aquifer in the Southern Adriatic Sea. At the Danish and Scottish sites the studies were continued right up until submission of a 'dry-run' permit application which was evaluated by a group of independent experts. The studies conducted at the other sites addressed some specific barriers related to the site characterisation methodology, such as screening of multiple options, fault geomechanics, fluid-rock interactions, presence of geological heterogeneity, trapping mechanisms, a Framework for Risk Assessment and Management and uncertainty management through *e.g.* sensitivity analyses. This sites portfolio thus gathers complementary sites that allow to cover the different steps of the site characterisation. Experience gained on the characterisation of these sites was used to refine and improve the SiteChar site characterisation workflow.

A comparative economic evaluation of the three offshore sites in the UK sector of the North Sea off Scotland, Southern Adriatic Sea and the Norwegian Sea and the onshore site in Denmark has been carried out at each site to analyse the cost of each phase of the storage project, from exploration and site characterisation, to site development, drilling and injection, up to monitoring and site abandonment. The variability of sites and their characterisation allowed to point out some critical and most influential parameters in the economic assessment of storage projects.

In parallel to technical issues, SiteChar considered the important aspect of the public awareness and public opinions of these new technologies. The assessment of current public knowledge and perception regarding the storage of CO_2 was conducted on the onshore Polish and offshore Scottish sites. A new format for public engagement was tested called 'focus conferences'. Impact of site-specific public engagement activities were assessed via the internet and information meetings. Two surveys were conducted to enable detection of changes in awareness, perceptions, *etc.* These exercises provide insight on the way local CCS plans may be perceived by the local stakeholders, and how to develop effective local communication and participation strategies.

Key lessons from the research conducted in SiteChar were developed by industrial and research partners within the consortium in consultation with regulators as technical recommendations for storage site characterisation and best practice guidance for storage permitting from the perspective of both applicant and regulator. They are presented as a best practice guide for policymakers and regulators at Member States and European levels, potential storage site developers and operators.

2 Summary description of project context and objectives

2.1 Context and SiteChar objectives

Warming of the climate system is unequivocal. CO_2 concentrations have actually increased by 40% since pre-industrial times, primarily from fossil fuels combustion that is expected to remain dominant in the fuel mix for decades. If unabated, CO_2 emissions will continue to rise likely exceeding the 2°C mean global temperature rise for the 21st century, and consequently likely leading to prejudicial environmental damage. Limiting the average global temperature increase to 2°C will require the deployment of a coherent portfolio of low-carbon technologies, amongst which Carbon Capture and Storage (CCS) is a critical component. CCS involves capturing CO_2 at coal- or gas-fired power plants, and factories (steel mills, cement plants, refineries), transporting it by pipeline or ship to a storage location and injecting it via a well into a suitable geological formation for long-term storage. In Europe, it is recognised as one of the key ways to reconcile the rising demand for fossil fuels with the need to reduce greenhouse gas emissions in the transition to a fully low-carbon economy.

In the last decade, research performed by industries, universities and research centres in Europe and worldwide in laboratories, natural CO_2 reservoirs and pilot sites, has demonstrated that geological storage of CO_2 is a viable and secure technology provided rigorous site selection and operations are undertaken. However, it is clear that the development of CCS projects has been slower than expected. Two key issues are recognised to constrain large-scale deployment of CCS: the costs for capturing CO_2 at large industrial sources and the public acceptance of storage in deep geological formations. In this context, the role of CO_2 geological storage, and more specifically of the characterisation of potential CO_2 storage sites, is crucial for the whole CCS chain notably for reducing the uncertainties on storage capacities for deep saline aquifers, de-risking CO_2 storage and ensuring a safe and permanent storage which is the key to gain public support.

The objective of the FP7 SiteChar project (January 2011 - December 2013) was to provide the key steps required to achieve readiness for large-scale implementation of CO_2 storage in Europe and establish the feasibility of CO_2 storage on representative potential CO_2 geological storage complexes suitable for development of CO_2 geological storage in the near term. Five sites were selected as test sites for the research, representing different geological and storage options across Europe, including depleted oil and gas reservoirs and deep saline aquifers, in both offshore and offshore contexts. More specifically SiteChar aimed to demonstrate, through complementary characterisations of five sites, the level of geological characterisation and assessment of long-term storage complex behaviour, rigorously tested in accordance with the regulatory requirements, so as to meet the criteria required to gain a storage permit. Secondly, SiteChar undertook the refinement of a complete generic storage site characterisation workflow, focused on the storage complex, from a static 3D earth model to hydrodynamic simulations of storage behaviour, monitoring programme planning, developing a Framework for Risk Assessment and Management, and including techno-economic evaluation and public outreach exercises. Thirdly, SiteChar planned to assess 'dry-run' storage permit applications by a group of geological experts and regulators in order to identify key lessons and hence improve the site characterisation workflow and the associated permitting process.

The SiteChar project was carried out by an interdisciplinary team of R&D institutions, academics and industrial partners, with a proven record in establishing best practice for site characterisation and having complementary thematic and regional experience as well as implementation of the first medium-scale storage demonstration projects. In the UK, the site characterisation was supported by the Scottish Government who facilitated an assessment of the 'dry-run' licence application by representatives of regulatory agencies for storage permitting in Scotland.

2.2 The SiteChar workflow

The SiteChar site characterisation workflow has been designed to support the development of the various European storage sites that will be needed for large-scale deployment of CCS. The objective of a site characterisation process is to demonstrate that the site has sufficient capacity to accept the expected CO_2 volume, sufficient injectivity to receive the expected rate of supplied CO_2 and appropriate containment to store the injected CO_2 for the period of time required by the regulatory authority, so as not to pose any unacceptable risks to human health, environment, or other uses of the subsurface. Several studies have been completed that address site characterisation for CO_2 geological storage and describe, to varying degree, the work to be conducted considering some aspects relevant to secure geological storage of CO_2 in a specific formation. Based on this knowledge and SiteChar partners experience, a preliminary workflow was drafted. It was to be applied on five putative storage sites representative of various geological contexts: hydrocarbon fields and deep saline aquifers, either offshore or onshore sites, and well spread in Europe. SiteChar planned to examine the entire site characterisation chain, from the initial feasibility studies through to the final stage of application for a storage permit, on the basis of criteria defined by the relevant European legislation, *i.e.,* including estimations of storage capacities, predictions of CO_2 plume migration in storage aquifers at basin or reservoir scale, evaluation of injection scenarios, risk assessment, development of the site monitoring plan, assessment of costs related to storage and public awareness. Insights and lessons learnt from the sites application were included in the final version of the workflow. The objective was to provide at the end of the project a detailed and tested understanding of the work required to obtain a storage permit, whilst promoting a clearer agreement between site developers, regulators and the public on methodologies for the selection and characterisation of appropriate sites for long-term safe CO_2 storage.

2.3 The SiteChar sites portfolio

The research conducted in SiteChar relied on the characterisation of five European storage sites considered as potential options for the development of CCS in the near term. These sites are representative of geological storage complexes where CCS is likely to develop. They comprise depleted oil and gas reservoirs and deep saline aquifers, in both offshore and offshore contexts, with different regulatory requirements, *etc*. Together the SiteChar sites portfolio gathers complementary sites allowing to cover the different steps of the characterisation workflow. At the Scottish and Danish sites, the site characterisation aimed to produce ‘dry-run’ storage permit applications to be evaluated by a group of independent experts and, for the UK site, by the competent authorities. The studies conducted at the other sites were designed to address some specific barriers related to the site characterisation methodology.

The UK northern North Sea site provides a template for the characterisation of large-scale CO_2 geological storage, based on a feasible site in the North Sea, Europe’s largest potential storage area. This is a multi-store site that comprises a deep saline aquifer together with an associated hydrocarbon field. This site provided the opportunity to perform a full-chain characterisation of an offshore multi-store site sufficient to prepare a ‘dry-run’ storage permit application. The main characterisation tasks were (i) building an attributed static geological model of the storage complex by integration of detailed and extensive data sets, (ii) short- to long-term fluid flow modelling of CO_2 injection into the hydrocarbon field and the aquifer to assess hydrodynamic storage capacity, near-field and far-field pressure changes; (iii) assessment of the site geomechanical stability; (iv) mitigation of risks to the containment of CO_2 in the subsurface; (v) design of a monitoring plan within a Framework for Risk Assessment and Management, (vi) economic analysis, viii) preparation and submission of ‘dry-run’ storage permit application to a group of experts and the competent authorities. In addition to these technical activities, public engagement activities were conducted on this offshore site.

The Danish Vedsted site is an onshore Upper Triassic-Lower Jurassic aquifer at 1800-1900 m depth, situated in the northern part of Denmark close to the Nordjyllandsvaerket power plant and previously identified as a possible option for full-scale demonstration project for CCS. This site also provided the opportunity to perform a full-chain characterisation of an onshore deep saline aquifer, up to the development of a ‘dry-run’ storage permit. The research on this site investigated different ways to supplement the sparse data usually available from saline aquifers. On this onshore site, there was a special interest in exploring the impact on the surrounding region, especially pressure development in the saline aquifer and any possible effects in the overlying layers. Main tasks were dedicated to (i) improvement of available static/facies/reservoir models to govern (ii) fluid flow simulation to investigate, amongst others, the pressure development, (iii) baseline monitoring and remediation plans, (iv) economic analysis and (v) submission of ‘dry-run’ storage application to a group of experts.

The Polish Załęcze-Żuchlów site is representative of sites in the Polish Lowland that offer a series of natural gas reservoirs with CO_2 storage potential. This site provided the opportunity to undertake the whole characterisation workflow from the first stages through to the development of an injection strategy for a cluster of two onshore depleted gas reservoirs. Main tasks were dedicated to (i) construction of the static geological model at basin and reservoir scales including assessment of the hydraulic connectivity (ii) fluid flow simulation and elements of geomechanics to evaluate the geomechnical integrity of the storage, (iii) study of permeability changes during CO_2 injection by laboratory experiments and numerical reactive flow simulation, and (iv) integrity analysis of the large number of wells existing in these depleted gas reservoirs. Public engagement activities were conducted on this onshore site, with the same process and the same timing as those conducted on the onshore Scottish site.

The Norwegian Halten Terrace/Trøndelag Platform is situated offshore Mid-Norway in an area containing gas with natural high CO_2 content that can be extracted and stored. This is an offshore multi-compartment site with both deep saline formations and dry structures with reservoir boundaries delimited by faults. These faults might influence possible migration of the planned stored CO_2 and possible fluid flow. The research on this site focused on the development of site characterisation procedures for a multi-storage complex with structural traps and/or open deep saline aquifer. Different simulation approaches were used to quantify CO_2 saturation and possible flow and leakage. Main tasks were dedicated to (i) simulations of CO_2 migration and leakage at a basin scale, (ii) fluid flow and pressure modelling with special emphasis on the storage capacity estimation and possible migration pathways, and (iii) development of monitoring plans enabling a safety and environmental impact assessment. A preliminary economic assessment of the site was also performed.

The Southern Adriatic Sea site is an offshore deep saline aquifer located close to the main Italian CO_2 emission power plant where energy company Enel has started a pilot plant for CO_2 capture in April 2010. The selected site consists of a structural trap in a carbonate saline aquifer. The Southern Adriatic site provided a good opportunity to develop a robust methodology for site characterisation for the purpose of CO_2 geological storage in these formations. The main objective of the research was to infer the effect that natural faults might have on migration of injected CO_2 and the effect that CO_2 injection might have on the stability of natural faults. Main tasks were dedicated to (i) construction of the static geological model at reservoir scale and (ii) coupled fluid flow and geomechanical modelling to predict the behaviour of the storage complex during CO_2 injection and assess its geomechanical integrity. A preliminary economic assessment was also performed.

2.4 SiteChar outcomes

SiteChar focused on specific aspects of the site characterisation that must be addressed before launching industrial-scale implementation of CO_2 storage in Europe so as to supply at the end of the project a methodological guide adapted to European specific geological and regulatory contexts for use by storage site operators and regulatory bodies.

Assessing the storage complex and site behaviour assessment – Site characterisation is a multidisciplinary process. To predict long-term future site performance, advanced dynamic modelling of the storage complex requires a detailed definition of the geological static model able to reproduce the distribution of the petrophysical/mineralogical heterogeneity of both reservoir, cap rock and overburden. This model has to be constructed at different scales, from reservoir- to basin-scale. Indeed, an important result of fluid flow simulation is the prediction of the CO_2 plume propagation and the induced pressure distribution. However, the overpressure resulting from CO_2 injection is strongly correlated with boundary conditions; it is thus crucial to provide quantitative boundary conditions from modelling at basin scale in order to estimate a realistic distribution of the pressure increase into the far field. This point, amongst others, is addressed within SiteChar. Impact of the pressure footprint of CO_2 injection on other uses of the subsoil, such as adjacent hydrocarbon fields, is a key consideration for regulators. When necessary, mitigation of the pressure footprint will have to be investigated. Geomechanical studies allow the characterisation of seal rock integrity in fractured cap rocks. Possible reactivation of existing faults or creation of new fractures resulting from the increase of pressure generated by CO_2 injection into the reservoir are important issues to be assessed in order to evaluate the geomechanical integrity of the storage. Geomechanical modelling also provides an estimation of crucial seal rock fracture pressure that is key for the integrity of the cap rock. In addition, modelling of fluid rock interactions allows a better understanding of the effect of CO_2 chemical reactions with reservoir rock and fluid on injectivity in the short term and storage integrity in the long term.

Techno-economic evaluation – An economic evaluation of the costs for site development, based on likely injection design, was conducted on four sites: three offshore sites in the UK sector of the North Sea off Scotland, Southern Adriatic Sea and the Norwegian Sea and an onshore site in Denmark. The variability of sites and their characterisation allowed for an interesting range for comparison. The SiteChar techno-economic assessment covers the exploration phase, the Front End Engineering and Design (FEED), the site development, the CO_2 injection phase and long-term monitoring. The analysis is performed on the full lifetime of the storage site up to state/agency transfer of liability. Understanding what makes the differences between the costs estimated on the different sites provides interesting outcomes, the aim of this study being to understand the most influential parameters in the economic assessment.

Public Awareness – Recently, the importance of public perceptions of CCS technology has become unequivocal with several CCS demonstration projects being delayed, postponed or cancelled following protests from the local population, notably in the Netherlands, Germany, France, Denmark and the US. Various causes may have contributed to this situation, *e.g.* a lack of initial public awareness, a negative perception of climate policies and new technologies in general, the limited public trust in local decision-making on CCS and a limited credibility of information on CCS. SiteChar aimed to advance on this crucial issue by conducting social site characterisation and public participation activities at two prospective CCS sites: the onshore Polish and the UK offshore sites. The first step provided a social characterisation of the areas through desk research, stakeholder interviews, media analyses, and survey amongst a representative sample of the local communities. This enabled identification of stakeholders or interested parties and factors that may drive perceptions of and attitudes towards CCS. Based on these results, a new format for public engagement named ‘focus conferences’ was tested at both sites involving a small sample of the local community with operators and authorities taking part in the discussion. The third step was dedicated to make generic as well as site-specific information available to the general and local public, by setting up a bilingual set of information pages on the SiteChar website suitable for a lay audience and organising information meetings open to all at both sites. Finally, a second survey amongst a new representative sample of the local community, largely identical to the first one, monitored changes in awareness, knowledge and opinions over time.

The SiteChar ‘dry-run’ storage permit applications – A key innovation of the SiteChar project was the development of internal ‘dry-run’ permit applications that were expected to provide a pragmatic and efficient approach to promote a more realistic permit application process and ensure that key lessons on best practices can be fully applied. Two contrasting sites, an assumed to be depleted hydrocarbon field and host saline aquifer sandstone in the UK northern North Sea and the Vedsted deep saline aquifer site in onshore Denmark, were selected for advanced site characterisation and development of ‘dry-run’ storage permit applications to be submitted to a group of experts and competent authorities. Developing ‘dry-run’ permit applications and undertaking independent reviews of these applications helped identify the best approaches to site characterisation enabling robust and defensible permit applications to be developed by storage operators in the near future. It was also hoped that relevant regulatory authorities will find the process useful for the identification of the necessary levels of evidence required to assess safety, containment and capacity of putative storage sites. The ‘dry-run’ process also allowed test and refinement of the SiteChar workflow for site characterisation. The review compared the ‘dry-run’ storage applications against the requirements in the EC Storage Directive, and the associated Guidance Documents and, for the UK site, the UK-specific guidance documents and derive feedback for competent authorities.

Guidelines for site characterisation and permitting – Key lessons from the research conducted in SiteChar were developed by industrial and research partners within the consortium in consultation with regulators as technical recommendations for storage site characterisation and best practice guidance for storage permitting from the perspective of both applicant and regulator. The aim was to produce a best practice guide for policymakers and regulators at Member States and European levels, potential storage site developers and operators.

3 Description of main S&T results/foregrounds

Over three years, SiteChar has integrated, improved, extended and tested standard site characterisation workflows, in order to establish the feasibility of geological CO_2 storage on representative potential CO_2 storage complexes suitable for development in the near term and hence facilitate the deployment of CCS in Europe. SiteChar has examined the entire site characterisation chain from the first initial stages up to the final stage of storage permitting, including technical, economic as well as societal aspects. The SiteChar research focused on five potential European storage sites, spanning a range of representative geological contexts, as test sites for the site characterisation workflow. Development of internal 'dry-run' storage permit applications, tested by relevant regulatory authorities helped to refine the storage site characterisation workflow and identify gaps in site-specific characterisation needed to secure storage permits under the EC Storage Directive, as implemented in 'host' Member States. At the end of the project, SiteChar produced a methodological guide adapted to European specific geological and regulatory contexts for use by prospective storage site operators and regulatory bodies. Feedback on the European regulatory framework was also produced.

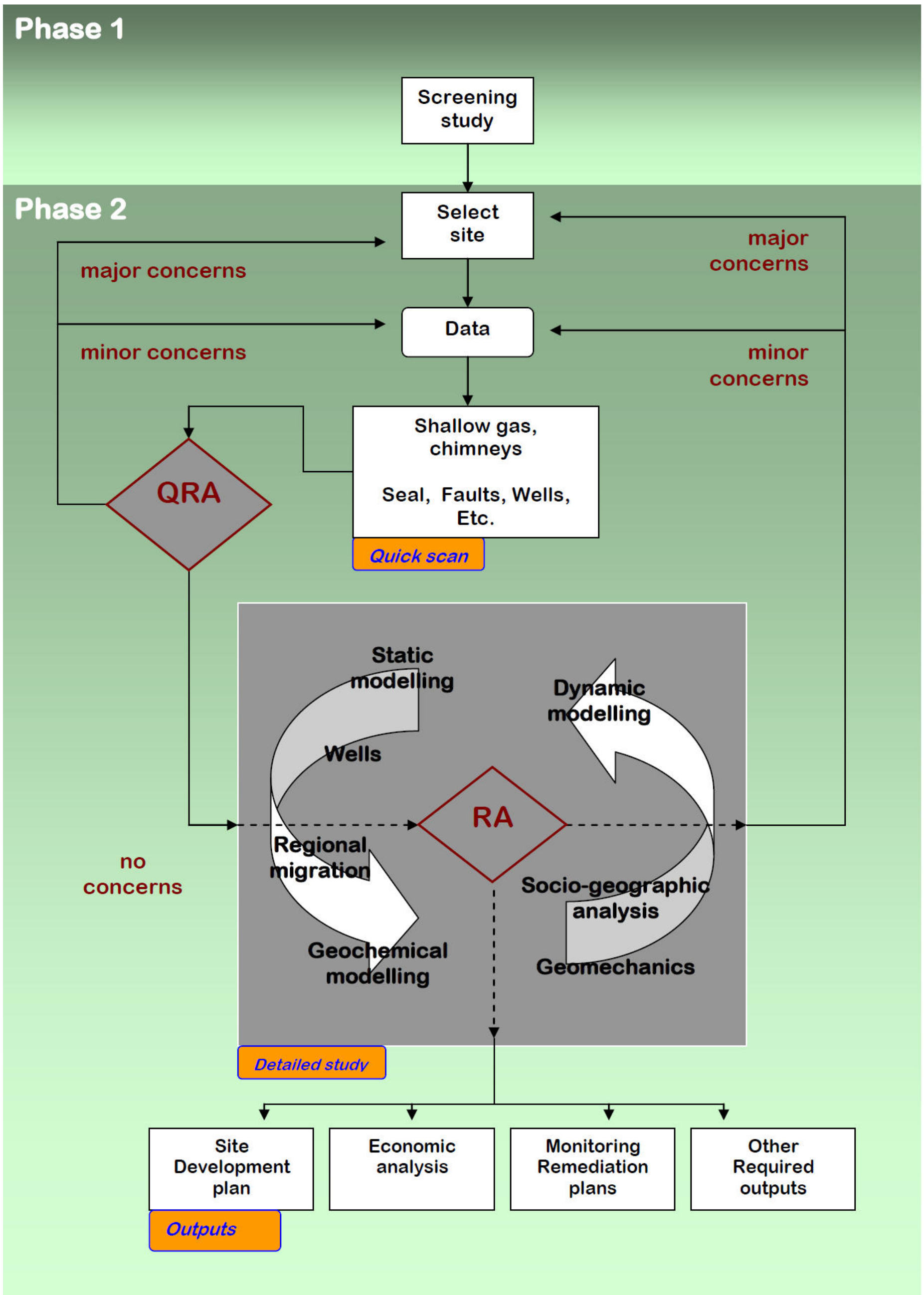
3.1 The SiteChar workflow

One of the main objectives of the SiteChar was to develop a workflow for site characterisation and risk assessment studies for the storage of CO_2 under the EC Storage Directive. This workflow is presented in SiteChar Deliverable D1.4 which is a public report available for download on the SiteChar website. It defines the work to be performed to comply with the EC Storage Directive and conduct efficient site characterisation studies to be presented to the competent authorities when applying for a storage permit. This workflow was applied and tested at five potential CO_2 geological storage sites representative of different geological contexts and the experience thus acquired was used to update the workflow.

The SiteChar workflow for CO_2 storage site characterisation provides a description of all elements of a site characterisation study, as well as guidance on these issues, to streamline the site characterisation process and to make sure that the output covers the aspects mentioned in the EC Storage Directive. Characterisation of a site relies on a number of steps that are performed in close coordination in the following order: (i) Data acquisition and quick analysis; (ii) Qualitative and quantitative risk assessment; (iii) Geological assessment; (iv) Hydrodynamic behaviour simulation; (v) Geomechanical assessment; (vi) Geochemical evaluation; (vii) Migration path analysis; (viii) Well integrity analysis; (ix) Monitoring and remediation planning. In addition to these steps, the following steps have also to be performed all in parallel to the characterisation: (x) Social acceptability analysis and (xi) Economic assessment. Characterisation of a site thus requires a multidisciplinary expertise based on a close cooperation between disciplines. SiteChar emphasised the need to share from the beginning of the project the purpose of the activities, their interdependencies, and any changes to the purpose during the progress of the investigations so as to provide an adequate qualification of all elements of the storage site in line with regulatory requirements.

SiteChar recommends a site characterisation driven by risk and uncertainty management, aiming to anticipate, reduce and mitigate risks and uncertainties. Clearly the site characterisation is site specific: even if the main steps to be achieved are the same for each site, the way to address each step depends on the site, the available data and the specific uncertainties and risks to be investigated. Indeed, a key learning of the SiteChar project is that characterisation of a site for the purpose of obtaining a CO_2 storage permit is a risk-based process with the objective of demonstrating safe and permanent storage. This means that focus should be put on issues that may lead to loss of containment. These issues include possible CO_2 leakage via the seal rock, fault or well, or laterally via a spill point, so as to (i) assess potential risks of impacts on humans, animals and vegetation, (ii) demonstrate absence of degradation of the quality of fresh groundwater by brine displacement and ground movement, (iii) demonstrate absence of damage of infrastructure, (iii) meet any specific legal and regulatory requirement. Risk analysis thus defines the focus of the site characterisation work that iteratively defines and constrains risks and intends to reduce their consequence and/or likelihood to acceptable levels.

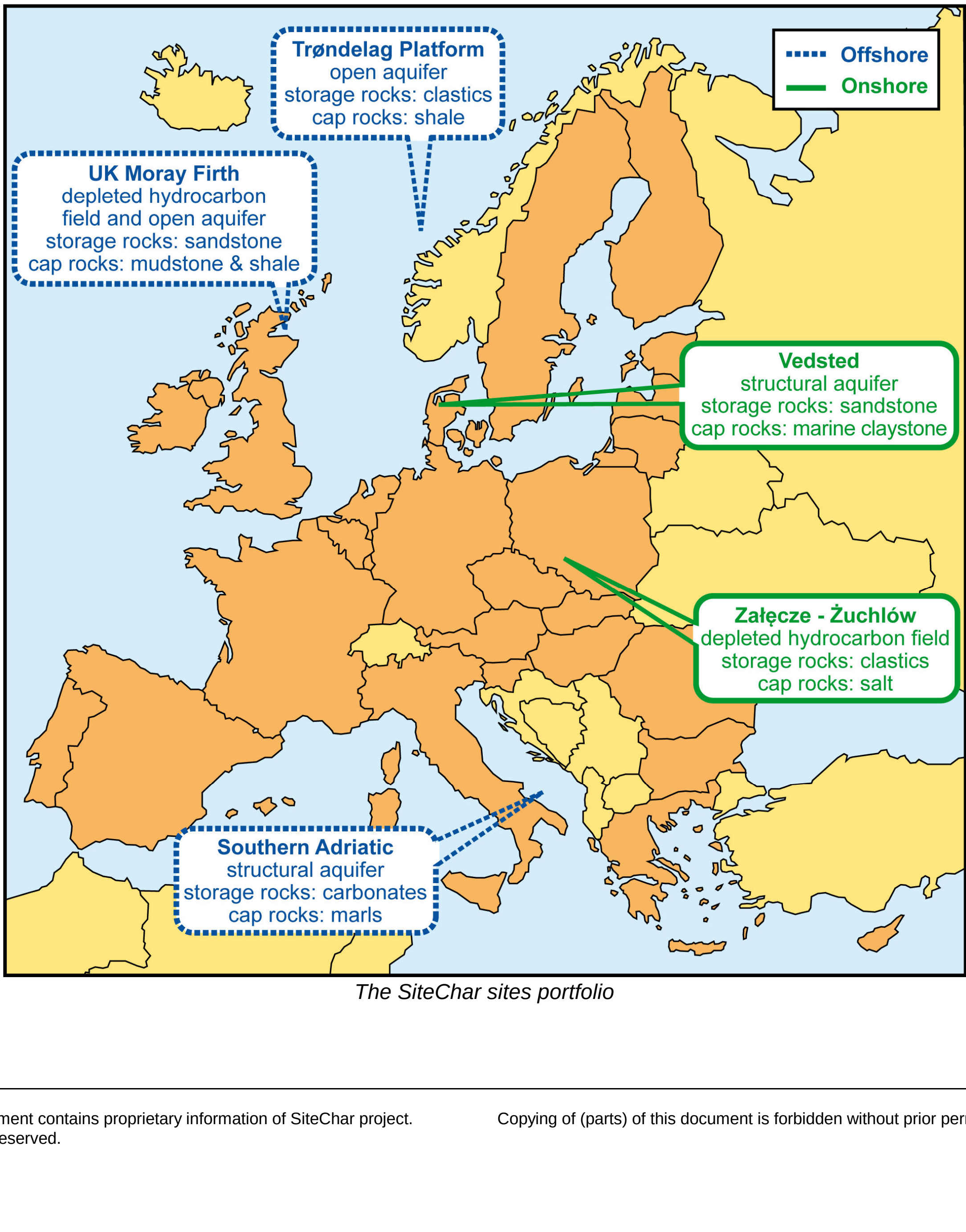
Discussions between the operator and the competent authority are considered beneficial to identify key areas requiring investigations to comply with the requirement of the EC Storage Directive. Indeed, even if the Annexes to the EC Storage Directive suggest an exhaustive program of investigation to be conducted, in practice, some parts of the proposed program might be more relevant than others. Therefore, it is advocated to consider the characterisation process as a mutual concern of operator and the competent authority. The specific investigations undertaken at a given site will therefore reflect the characteristics of the site, the jurisdiction within which it resides and the storage concept being proposed.



The SiteChar Workflow for site characterisation

3.2 The SiteChar sites characterisation

The research conducted in SiteChar was based on the characterisation of five representative European sites feasible for CO_2 geological storage: a northern North Sea multi-store site offshore Scotland; an onshore aquifer in Denmark; an onshore gas field in Poland; an aquifer offshore Norway and an aquifer in the Southern Adriatic Sea. At the Danish and Scottish sites, the characterisation has been conducted as far as possible in the framework of a research project so as to develop 'dry-run' storage permit applications that have been evaluated by a group of independent experts. The studies conducted at the other sites focused on specific barriers related to the site characterisation methodology, *e.g.* assessing the well integrity of a depleted hydrocarbon field with quite a large number of abandoned wells, estimating the storage capacities in a multi-store complex with structural traps and open saline aquifers, evaluating the geomechanical stability of a carbonate reservoir. The summary of the characterisation of these sites and the lessons learnt regarding the application of the workflow are presented in SiteChar Deliverable D2.1 which is a public report available for download on the SiteChar website.



The SiteChar sites portfolio

'Dry-run' application for a CO_2 storage permit for the SiteChar UK northern North Sea site

Context for the UK North Sea site – Depleted offshore hydrocarbon fields are proposed as storage sites for CO_2 captured by UK CCS demonstrator projects. The theoretical storage capacity of brine-filled sandstones (*i.e.,* deep saline aquifers) far exceeds that of smaller but much better-known hydrocarbon fields. Site characterisation of a UK offshore site in SiteChar looks ahead to commercial-scale storage in a mature CCS industry where CO_2 is contained in a multi-store site, which comprises both a depleted hydrocarbon field and the surrounding saline aquifer sandstone. Previous research studies have deemed the Captain Sandstone, in the Outer Moray Firth offshore eastern Scotland, to be feasible for storage and justifying further investigation for CO_2 storage. Additionally, two demonstrator sites for CO_2 geological storage have been proposed within the Captain Sandstone during the progress of the SiteChar research project. The SiteChar investigation benefitted from existing research knowledge and availability of a basin-scale model of the Captain Sandstone and an abundance of data from hydrocarbon exploitation on which to base detailed characterisation activities.

Objectives and activities for characterisation of the multi-store site – The objective for characterisation of the UK multi-store site in SiteChar was to prepare, as much as possible within the resources of a research project, a 'dry-run' application for a CO_2 storage permit. The components of a storage permit application are based around a process of assessment of risks to the secure containment of CO_2 within the storage site. Site characterisation activities for the UK site in SiteChar were targeted to reduce and mitigate those risks and increase certainty in knowledge of the prospective storage site. The North Sea is an active hydrocarbon production province where the potential interaction between future CO_2 storage sites and existing hydrocarbon fields remains unknown. An additional important objective for the UK North Sea site was thus the investigation of the predicted relationship with hydrocarbon fields in the immediate vicinity of the prospective storage site. A hydrocarbon field hosted within the Captain Sandstone was selected for the SiteChar research, the Blake Oil Field, because it has a storage capacity large enough to warrant development as a CO_2 storage site and, most importantly, sufficient accessible and publicly available data from hydrocarbon exploration for the research project. For SiteChar, the field was assumed to be depleted of oil.

A risk-assessment based characterisation – An initial assessment by the site characterisation researchers in SiteChar identified those perceived risks to the secure containment of CO_2 within the multi-store site. They used their expert knowledge and judgment to assess whether the risks were likely to occur and, in the case they did happen, the consequence to the storage site. Those technical risks that were ranked most highly were the target of the investigations, with the intention to reduce or mitigate the risk and also to increase certainty in understanding of the site. Data from hydrocarbon field exploitation were interpreted to construct a detailed computer model of the geology of the site. The effect of CO_2 injection was predicted using computer software developed in the oil and gas industry. Different injection scenarios were tested to examine, compare and select a scenario most suitable for the secure containment of CO_2 at the multi-store site. Techno-economic data were compiled for the selected scenario. Further optimisation of the injection scenario is however recommended. Detailed investigation of the possible effects of CO_2 injection was undertaken, including the increase in reservoir pressure, geochemical reaction between the storage site rock and CO_2, whether abandoned oil and gas wells or naturally occurring geological features might act as flow pathways for the stored CO_2 and likely flow pathways if the site were substantially and excessively overfilled. The resulting predictions were used to inform design of both the storage site and the injection scenario to reduce risks to the secure containment of CO_2. A reassessment of the risks after completion of the technical site characterisation identified additional activities to further reduce risk, preventative measures to be implemented before and during site development, monitoring of risks that had not been mitigated and corrective measures if any of the risks did happen. One of the proposed activities to monitor and verify the predicted performance of the site is based on appropriate seismic survey, the results of a detailed site-specific investigation indicating this monitoring method is feasible for the multi-store site even though it lies beneath a strong acoustic reflector. The risk assessment-based process also informed definition of criteria by which to demonstrate that the site complies with regulators requirements (Permit Performance Conditions). Once these criteria are met, after injection has ceased, the site will be able to be closed and responsibility relinquished to the state.

Implications to storage site design and management from site characterisation – An annual rate of CO_2 injection of five million tonnes, appropriate for commercial-scale storage supplied from sources onshore Scotland, was assumed for a period of twenty years. Increased pressure associated with injection of CO_2 at this 'commercial' rate was found to be the main factor guiding the selection of an injection scenario and determining design of the storage site. Injection into the hydrocarbon field, rather than into the saline aquifer sandstone, and simultaneous production of water from the sandstone down-dip from the storage site is needed to manage the increased pressure due to CO_2 injection at the assumed rate. Predicted pressure increases for this injection scenario are 37% of the maximum allowable pressure to ensure there is neither fracturing of the cap rock nor movement on existing faults and to minimise any uplift of the sea bed. The maximum predicted pressure is also less than the cap rock capillary entry pressure. Changes in the storage capacity, due to mineral growth within the storage sandstone whether CO_2 was injected or not, were predicted to be negligible and over thousands to millions of years. During the twenty-year period of injection the CO_2 gas migrates into and mainly within the Blake Field boundary. Up to 2% of the CO_2 dissolves in the brine contained within the sandstone. Once injection ceases, migration of the CO_2 gas stops and the rate of migration of the dissolved CO_2 plume slows. Forty years after injection ceases, the gas is retained within the field, the dissolved CO_2 plume is stable; it extends less than two kilometres beyond the field boundary and does not affect other hydrocarbon fields in the vicinity hosted within the Captain Sandstone. The impact of increased pressure at the commercial rate of injection is minimised by water production. Little pressure change related to storage site operation is predicted twenty kilometres up-dip in the vicinity of the Captain Field. In the un-optimised injection scenario an initial drop in pressure is predicted down-dip in the vicinity of the Atlantic and Cromarty fields, with pressure gradually increasing to slightly over initial values during the period of injection. Once injection ceases the pressure rapidly reduces, with a minor residual value above the initial pressure remaining to the north-east of the storage site.

The multi-store site 'dry-run' storage permit application – A 'dry-run' storage permit application for the SiteChar multi-store site in the UK northern North Sea was prepared from the results of the risk assessment-led site characterisation activities. Most of the components required by the EC Storage Directive on the geological storage of carbon dioxide that are within the scope of a research project are included within the application. A storage permit would not be awarded on the basis of the 'dry-run' application prepared in SiteChar; site characterisation research in the project is a first iteration of activities needed to increase knowledge and reduce risks to a level that is 'as low as reasonably possible'. Many times the amount of investigative effort than the resources available in SiteChar would be required to meet this standard. However, the risk assessment-led process has identified issues that would need to be addressed for a 'real' storage permit application. Site characterisation of the offshore UK multi-store site has increased understanding of a feasible site, reduced risks and uncertainties and identified additional issues from the results of the research. Issues arising from the research would be relevant to any prospective site in a mature hydrocarbon province, such as access to oil and gas industry data or storage site interaction with producing fields. Some issues are site specific, such as the feasibility of seismic survey monitoring of a depleted oil field beneath a strong reflector. Throughout, the 'dry-run' storage permit application identifies issues that remain to be fully addressed by site characterisation. Additional investigations are proposed by SiteChar researchers that might be followed to increase understanding of the site and reduce risk to as low as reasonably possible for a 'real' storage permit application.

Conclusions – Characterisation of the offshore UK multi-store site in the Outer Moray Firth demonstrates there is sufficient publicly available data within a mature hydrocarbon production province to investigate and prepare an outline storage permit application within research resources. Even in an area of abundant legacy data, not all site-specific data sought for characterisation were publicly available. The SiteChar research has identified additional activities to further reduce uncertainties, mitigate and monitor unmitigated risks that would be needed for a 'real' permit application for a storage site. Characterisation of the UK multi-store site has enabled preparation of most of the key components required by the EC Storage Directive on the geological storage of carbon dioxide although some, such as details of financial security, are beyond the scope of a research project. Characterisation to inform preparation of a 'dry-run' storage permit application demonstrated the very close interaction and integration of emerging technical findings needed across all site characterisation activities. Final decisions on essential elements of storage site design and predictions of the storage performance could not be made until the results of all technical investigations were available, the implications discussed and reassessment of risks undertaken.

'Dry-run' application for a CO_2 storage permit for the Vedsted site, Denmark

Context for the Vedsted site – From 2007 to 2011, Vattenfall A/S planned to develop a full-scale demonstration project for CCS at the Vedsted site in Denmark. As a consequence of Danish political decisions on CCS and re-organisation within the Vattenfall company, the plan for the demonstration project was stopped in 2011, but this site can however be considered as a 'realistic' case for CO_2 storage. The Vedsted structure is close to the Danish power plant Nordjyllandsværket which has a yearly CO_2 emission of approximately 2 Mt/year. A first estimate for the storage capacity for the site indicated that the storage capacity exceeds the potential captured CO_2 volume from the power plant in a forty years lifetime and a nearby cement industry with emissions of up to 1 Mt/year could potentially be phased in. The total amount to be planned for could be as high as 3 Mt/year. Distance of transport is around 30-35 km and construction of a pipeline could be envisaged. The characterisation of the site should meet the challenges with the sparse data set available for deep saline aquifers and evaluate that the expected stream of captured CO_2 could be safely stored.

Implications to storage site design and management from site characterisation – Coupled geomechanical and fluid flow modelling provided first estimates of pressure footprints from the injection process. Results indicated that risk of leakage through fault reactivation is unlikely to occur for the injection scenarios examined with or without water production for pressure management. Water production can mitigate undesirable pressure increase in the surroundings as well as suppress ground uplift. Model results showed up to a 30% reduction in ground up lift with a 70% voidage balance through water production. Pressure footprint modelling results are strongly dependent on setting up proper model boundary conditions, and use of large scale regional models surrounding a site specific model can govern dynamic boundary conditions for site modelling.

Recommendations for site integrity – In contrast to storage in a depleted hydrocarbon reservoir, only a single or few wells penetrate the overburden and reservoir interval minimising potential risk of leakage. However, the abandonment state of old exploration wells might be a challenge to resolve. An evaluation of the Vedsted-1 legacy well placed on the apex of the Vedsted site resulted in a recommendation for re-intervention and proper abandonment of the well based on present day technology and regulation. The recommendation was based on both economic and technical assessments. As Vedsted is an onshore storage site, situated in a deep saline aquifer, special emphasis was put on the monitoring plan. Baseline monitoring data are crucial to justify any irregularities. A detailed geochemical baseline study was performed within SiteChar at the Voulund Agricultural research site (central Denmark), which was used as a natural analogue of the near surface environment. Base line monitoring field experiments resulted in recommendations for designing future base line surveys for onshore storage sites; different land-use types must be identified and any seasonal variation must be captured as well as 'unexpected' events. To capture seasonal variation in soil gas fluxes, a monitoring period covering only a single year was assessed to be insufficient.

The deep saline aquifer 'dry-run' storage permit application – The 'dry-run' permit application process demonstrates that close cooperation between all technical disciplines is crucial during all phases of the process to secure a successful outcome. Risk assessment(s) in the early state of the application process was important to define the critical points for the specific storage project and helped focus the different studies to be included in to the final application. It is assessed that the SiteChar workflow template helps balance the work effort and the timing of the process. An important result and recommendation from the specific 'dry-run' application process is the identified lack of firm definition of the storage complex in the EC Storage Directive regarding pressure footprint on the surroundings. It is not clear how much pressure can increase on the storage complex delineation, which can be imperative especially for onshore aquifers.

Conclusions – Characterisation of the Vedsted site demonstrates that onshore storage in a saline aquifer sandstone should be possible. Preliminary modelling can be produced from sparse data and incremental phased development is proposed to progressively provide information to improve future operations and extrapolations of site performance. This will allow capture of the early reservoir response data for incorporation in the reservoir modelling and performance matching and provide and improve future operations and extrapolations of site performance. Preliminary modelling can be strengthened by incorporating integrated knowledge of the surrounding sedimentary settings even if the geological understanding is on a regional scale.

Characterisation of the Załęcze and Żuchlów gas fields, Poland

Context for the Załęcze-Żuchlów site – The Załęcze-Żuchlów site is representative of sites in the Polish Lowland, which offer a series of natural gas reservoirs with CO_2 storage potential. This site lies 60 km north of Wroclaw and 100 km south of Poznan where several CO_2 production centres are located. The main objective of the characterisation of the Załęcze and Żuchlów depleted gas fields within SiteChar was the confirmation and verification of the technical opportunities of CO_2 injection and the identification of key risk factors of a potential CO_2 geological storage project. The Załęcze and Żuchlów depleted gas fields, as other gas fields in the area, have been operated for about 30 years. Thirty-five production wells were drilled in the reservoirs. The characterisation of the Polish site was conducted on a large amount of data, however of varied quality. Most important data, *e.g.* geological characteristic of the investigated area, well logs, results of the laboratory analyses and well tests, were collected by the site operator. In all analysed wells, except one, the well logs were made in the years 1971-1979, therefore their quality is closely connected to the methods and the technological level of measuring and recording equipment available at that time, which was actually quite low compared to the present state. In addition, good quality seismic data and ground surface leveling data were actually rather limited.

Potential for CO_2 geological storage – Research activities conducted within SiteChar showed that the Załęcze-Żuchlów site presents a significant potential for geological storage of CO_2. The capacity of the Załęcze and Żuchlów gas fields was estimated sufficient to store the amount of CO_2 envisaged to be captured at a coal-fired power plant in close proximity to the site. The sealing capacity of the cap rock was estimated to ensure secure CO_2 storage and geomechanical simulations did not predict relevant damage to cap rock integrity provided the reservoir pressure remains below the initial pressure. However, these assessments have to be taken with care, taking into consideration the uncertainty on the continuity of the Zechstein cap rock above the reservoir and the lack of information on detailed fault geometry and on fault properties.

Assessment of possible CO_2 injection impact – Numerical simulations of the geomechanical behaviour of the site in the case of natural gas production and CO_2 injection allowed to estimate the extent and magnitude of stress changes around the gas reservoir, the geomechanical effects on top seal rocks as well as the induced subsurface and surface deformation. These simulations showed that vertical stress perturbations around the compacting reservoir follow the general pattern of unloading of the overburden above the reservoir and loading of the side-seal near reservoir edges. Deviations were observed in the top seal rocks above the reservoir due to the undulating shape of the reservoir top that makes local stress concentrate above surface peaks and depressions. It was concluded that fault and cap rock integrity at the Żuchlów site did not present any risk during the period of gas production and would neither during the scheduled CO_2 injection operation provided that the reservoir pressure remains below the initial pressure. It was however pointed out that this fault stability assessment has to be considered with care since only regional faults were considered due to the lack of high quality seismic data that did not allow to develop a more detailed field scale faulted model. Moreover mineralogical laboratory analysis as well as light microscopy scanning electron microscopy showed that, at least in the sampled range, the reservoir is characterised by quartz sandstones containing minor amounts of ankerite/dolomite and clay minerals. The porosity was estimated moderate to high, but the permeability was found low. Combined laboratory and simulation work gave a good overview of the reactivity of the reservoir formation in the case of an injection of solubilised CO_2 containing a fraction of O_2. In particular it showed the possible establishment of a ring of reactivity around the well that could affect the reservoir even during the injection phase. This analysis should be completed with a full-size 3D simulation taking in account the reservoir heterogeneity so as to be able to analyse with precision the potential evolution of the storage site and its effects on the petrophysical, mineralogical and geomechanical properties.

Recommendations for well integrity – Possible leakage through existing wells was estimated as the main risk to the integrity of CO_2 storage in the Załęcze and Żuchlów reservoirs. Laboratory experiments showed that CO_2 corrosive atmosphere reduces the strength of hardened sealing slurries. Cements were classified according to their resistance to corrosion in a CO_2 environment. Simulations of CO_2 leakage showed that the overall amount of CO_2 leaked through one leaking well is not significant. For abandoned wells located within the envelope of the CO_2 plume, it is suggested to monitor leakage by chemical monitoring of the soil and groundwater directly above and adjacent to the abandoned wells. Monitoring in a confined aquifer above the CO_2 reservoir is also recommended. In the case significant leakage is detected, remediation actions such as re-entering the well, milling out existing plugs/well section(s) or even adapting the injection strategy to avoid migration of the CO_2 plume towards the well are proposed.

Conclusions – A comprehensive but still preliminary characterisation of the Polish site has been conducted relying on a large amount of data of however various quality. The capacity of the Załęcze and Żuchlów fields was estimated sufficient to store the envisaged amount of CO_2 to be captured of a coal-fired power plant in the proximity of the site. The cap rock was estimated to allow a secure CO_2 storage provided the reservoir pressure remains below the initial pressure. However these assessments have to be taken with care considering the uncertainty on the continuity of the Zechstein cap rock above the reservoir, the lack of information on faults geometry and faults properties, the *in situ* stress field, *etc.* No surprisingly loss of well integrity has been pointed out as the main risk for CO_2 storage. However even if some generic classification of wells and some generic scenarios have emerged, a definite assessment calls for the evaluation in more detail of all individual abandoned wells, which will require considerable efforts. Characterisation of the Polish site emphasised the need for sufficient reliable data at each step of the process, even in the case of depleted gas reservoirs that have previously been investigated by the oil and gas industry. Higher quality data would be welcome at the Załęcze-Żuchlów site, in particular high-resolution 3D seismic data acquisition to interpret fault geometry; ground surface levelling and acquisition of satellite data to support validation of geomechanical models; detailed analysis of wells in the extension of the CO_2 plume. The work conducted within SiteChar highlighted the need for a close cooperation between specialists covering different skills from geology, petrophysics, reservoir engineering and reservoir simulation.

Characterisation of the Trøndelag Platform site, Norwegian North Sea

Context for the Trøndelag Platform site – The Trøndelag Platform, offshore Mid-Norway covers an area of more than 50,000 km^2 that contains gas with naturally high CO_2 content that can be extracted and stored. It is considered as a possible area for CO_2 storage because two promising potential storage units of significant thickness are present within the middle Jurassic sedimentary layers, the Ile and the Garn Formations. These formations, which contain main oil and gas bearing reservoirs on the Halten Terrace area, have good to excellent storage characteristics. In addition they are relatively shallow buried (less than 2,000 m). The overlying low-permeable clastic rocks, which cover the whole investigated area and have a reported thickness up to 1,650 m, will most likely provide an effective seal rock. However, they are thinning towards east and intersecting with Quaternary sections close to the Norwegian coast so possible migration routes in the storage unit were very important to study.

Lessons learnt from simulations of CO_2 injection with various modelling tools and at different scales – Different modelling approaches have been applied to simulate CO_2 injection in the selected sites of the Trøndelag Platform, focusing on CO_2 containment and potential migration paths, as well as overpressure development. Several injection sites were evaluated based on basin-scale modelling with and without loss functions and reservoir modelling. The results showed large volumes for storage, with low pressure build-up. Due to the limited data (only three wells), the heterogeneity of the storage formation could not be adequately represented in the models. To address this uncertainty, a sensitivity study was conducted to evaluate the likely impact on the simulation results. CO_2 migration and pressure modelling has been carried at basin scale using different methods and reservoir scale. In general at basin scale, storage unit quality and capacity is excellent; under industrial injection scenarios of 1 Mt/year over forty years, no CO_2 migrates out of the enclosures. If injection volumes are increased by 5-fold to 5 Mt/year still over forty years, the CO_2 phase starts to spill from the initial entities. It is observed that CO_2 migration predicted by simulators that do not take residual trapping into account is higher than predictions by those in which such loss functions are implemented. At field scale, a synthetic dataset derived from data of a producing gas field was used and compared to a simplistic ´tank model´. Simulations at basin and reservoir scale showed the same pressure distribution with increased pressure in the compartment where CO_2 is injected. The basin-scale simulator however gave a simplified picture with a pressure increase in the whole injection cell, but a better prediction over large periods (hundred years and more). It was also observed that the 'tank model' led to a lower estimate of the amount of CO_2 stored as structure and reservoir properties are not considered. Finally CO_2 injection simulations suggested that a total of 120 Mt of CO_2 could be injected in the investigated area, at a rate of up to 4 Mt/year over 30-year period. The resulting pressure increase at the reservoir remains below 50 bar, even around the injection well where it is maximum. In addition, techno-economic analysis was carried out for the whole Trøndelag Platform area. It showed that the main cost drivers for CO_2 storage are drilling and completion of wells, subsea installations, site characterisation and engineering and the seismic monitoring.

Recommendations for monitoring – A generic monitoring plan has been derived for the Trøndelag Platform with example from the Alpha structure, that is flexible enough to be applicable to other identified storage sites in the Norwegian sector and that would cope with any deviation between observation data and predictive models. The main emphasis is put on repeat 3D seismic and pressure and temperature monitoring at the injection well. A generic remediation plan has also been proposed based on site specific containment risks as well as more generic scenarios for contingency monitoring.

Conclusions – The Trøndelag Platform is a virgin area that has been characterised on the basis of publicly available data in order to investigate a new prospective storage area. Different modelling approaches have been applied to simulate CO_2 injection in the selected sites of the Trøndelag Platform, focusing on CO_2 containment and potential migration paths, as well as overpressure development. From this study, the Garn Formation at the Trøndelag Platform seems well suited for injection and storage of CO_2 on an industrial scale over a period of forty years since this formation presents excellent porosity and permeability, adequate thickness and a low number of faults. In addition, the Garn Formation is overlain by thick shale sequences, further reducing fault leakage risk and also suggesting a low risk for cap rock leakage. Several injection sites were evaluated using basin modelling tools with and without loss functions as well as reservoir modelling software. Modelling of CO_2 injection showed large volumes for storage, with low pressure build-up. Due to the limited data (derived from only three wells), the heterogeneity of the storage formation could not be adequately represented in the geological model but a sensitivity study provided an alternative by evaluating its likely impact on the predictions of the storage behaviour.

Characterisation of the Italian offshore site, Southern Adriatic Sea

Context for the Southern Adriatic Sea site – The Southern Adriatic Sea site is a structural trap in a carbonate saline aquifer, close to the main Italian CO_2 emission power plant (*i.e.,* Federico II power plant in Brindisi) where energy company Enel started a pilot plant for CO_2 capture in April 2010. It is one of the biggest power plants in Italy that is characterised by very high CO_2 emissions, which amount to more than 15 Mt/year in 2004 which is the highest emission rate in Italy. The deep saline aquifer investigated within SiteChar is located only a few tens of kilometres from the thermoelectric power plant. It is the nearest amongst the potential sites for CO_2 geological storage in Italy. Thus, even if there is currently no precise plan, CO_2 storage in the identified structures of the Southern Adriatic offshore would represent a good opportunity to apply CCS at an industrial level and a strong contribution to the reduction of national CO_2 emissions. On the basis of publicly available data, the characterisation conducted in SiteChar aimed at a qualitative assessment of the Southern Adriatic Sea offshore area as a potential site for CO_2 geological storage. A real feasibility would however require a higher level of characterisation, starting from the acquisition of new data, such as higher resolution seismics and core samples of the reservoir and cap rock formations.

Lessons learnt from the Southern Adriatic Sea – The Southern Adriatic Sea site is specific since the reservoir is a carbonate formation. Investigation of carbonate rocks as potential reservoirs for CO_2 storage requires the classification of the pore space, which controls the petrophysical parameters of permeability and saturation. In addition, the wide range of pore size and the heterogeneous distribution of the porosity, through matrix and grains in carbonate rocks, make the determination of the effective porosity very difficult. Understanding the behaviour of the CO_2 plume in such a lithology thus requires accurate modelling. In deep saline aquifers, lack of direct borehole measurements creates specific issues that have been addressed through a sensitivity analysis approach to estimate the impact of the uncertainties related to petrophysical properties on the estimated storage behaviour. The research on the Southern Adriatic Sea site focused on the investigation of the geomechanical and hydrodynamic behaviour of the storage complex due to the CO_2 injection in a specific reservoir consisting of fractured carbonate formations with special attention to the effect that natural faults and fractures may have on CO_2 migration, and the effect that injection might have on the stability of faults. The assessment of the geomechanical behaviour of faults has been performed via hydro–geomechanical weak coupling, while modelling fluid flow inside faults. Fluid flow and geomechanical parameters were derived either from laboratory measurements performed on samples from a reservoir analogue, or data derived from published literature. Various representations of faults were integrated in the model to simulate fluid flow along the fault plan and stress evolution resulting from CO_2 injection. Various scenarios were also simulated to take into account the uncertainties in the petrophysical and geomechanical properties of the model, including different states of faults (*i.e.,* open, closed or mid-opened), various stresses (*i.e.,* normal faulting, or shear stress at a range of angles) and various fluid flow parameters. Post-processing analysis of geomechanical criteria showed that the Rovesti fault, which is located near the injection well, remains below the chosen Mohr-Coulomb criteria, concluding to no risk of potential damage, on the basis of the data that were available.

Conclusions – The work performed within the SiteChar project represents the first attempt to apply the full characterisation workflow in the Southern Adriatic area which might represent an opportunity to launch the first CCS project in Italy, taking advantage of the vicinity of the storage site to the one of the major Italian power plants. This is a preliminary study in which uncertainties were mainly associated to the scarcity and sparseness of available data, in particular, petrophysical properties and fault transmissivity. The approach adopted in SiteChar was to simulate several scenarios varying the petrophysical properties, the number of injection wells and fault characteristics. The fluid flow simulations provided conflicting results, strongly related to the simulated scenario. It is important however to note that, in the ‘worst case’, *i.e.,* when faults are open to fluid flow and when the most cautious petrophysical properties derived from well logs analysis are used, the CO_2 plume reaches the sea bottom thirty years after the start of injection. This scenario is far from the real envisaged scenario that considers ten years of injection. Geomechanical simulations performed to assess potential fault damage showed that the Rovesti fault, which is the closest to the injection well, should not present any risk of damage for all the considered scenarios and assumed stress regimes. A critical analysis of fluid flow and geomechanical simulation results led thus to consider the Grazia structure as a suitable site for a demonstration project, able to store a total amount of 10 Mt of CO_2 at an injection rate of 1 Mt/year during ten years. The entire project duration was estimated to forty years, five years for exploration followed by five years of site development, ten years of injection and twenty years of storage before the site liability transfer to the state. The characterisation of the Italian case underlined some issues related to the site characterisation workflow; in particular, the need to discuss with the industrial partner scenarios appropriate to the characteristics of the closest power plant. In addition some data, in particular those related to petrophysical and geomechanical properties, were scarce; site characterisation required additional data derived from literature as well as sensitivity analyses to infer the effect of the associated uncertainties. SiteChar has also evidenced some critical aspects of the characterisation of carbonate formations. Scientists and decision makers involved in such feasibility studies would be faced to similar uncertainties and similar issues for the risks evaluation as those addressed in SiteChar. Finally, the methodological approach developed in SiteChar should be considered for further investigations in the Southern Adriatic area. At the same time it represents a case history for any storage project in a carbonate reservoir.

3.3 Public outreach activities

Context – At the local level, public support has proven crucial for the implementation of CCS demonstration projects, as illustrated by the public’s reaction to CCS projects. Although there are also examples in which local demonstrations received public support or have at least not been rejected, such as the Lacq project in France, experiences emphasise that if local CCS projects are to take off, the public should be consulted and involved in decision-making about prospective CCS projects. Whereas no method exists to guarantee public acceptability of any project, a constructive stakeholder and citizen's participation process does increase the likelihood thereof. SiteChar has addressed this issue by conducting social site characterisation and public participation activities at two prospective CCS sites: an onshore site and an offshore site. The onshore site is the Załęcze-Żuchlów site in Poland and the offshore site is the North Sea Moray Firth site in Scotland, for which the research focused on the communities in Morayshire.

The SiteChar process for enhancing public cooperation – The research consisted of four steps over a time period of 1.5 years, from early 2011 to mid-2012. The first step consisted of four related qualitative and quantitative research activities: desk research, stakeholder interviews, media analyses, and a survey amongst a representative sample of the local community. The aim was to identify (i) stakeholders or interested parties and (ii) factors that may drive their perceptions of and attitudes towards CCS. Results were used as input for the second step, in which a new format for public engagement named 'focus conferences' was tested at both sites involving a small sample of the local community. The third step consisted in making generic as well as site-specific information available to the general and local public, by (i) setting up a bilingual set of information pages on the project website suitable for a lay audience and (ii) organising information meetings at both sites that were open to all who took some interest. The fourth step consisted of a second survey amongst a new representative sample of the local community. The survey was largely identical to the initial survey to enable monitoring of changes in awareness, knowledge and opinions over time. Additionally, the second survey was used to obtain a quantitative measure of some commonly held public perceptions about CCS. In part these perceptions were derived from the focus conferences and in part from previous research. Results provide insight on the way local CCS plans may be perceived by the local stakeholders, how this can be reliably assessed at an early stage without raising unnecessary concerns, and how results of this inventory can be used to develop effective local communication and participation strategies. The summary of the SiteChar public participation activities is presented in SiteChar Deliverable D8.5 which is a public report available for download on the SiteChar website.

Social maps of the SiteChar Polish and UK sites – Relevant developments in the area that may affect the opinion about local CCS plans at the Polish site were unemployment, lack of infrastructure, presence of a Natura2000 area, and ongoing activities in brown coal mining and shale gas. At the Scottish site, main issues were unemployment, developing the area for tourism, presence of many other energy operations, and activities related to marine life/fishing. Preferred and trusted communication channels and stakeholders were at both sites the internet, local newspapers, councillors, and political parties. Local radio stations were also mentioned as trusted information source at the Polish site. The level of awareness and knowledge of CO_2 and CCS was very low at the Polish site, with at the end of the research still 78% reporting 'never heard about it'. Awareness was quite low at the Scottish site: at the end of the research still 53% reported 'never heard about it'. Some misconceptions on CCS, CO_2, and related concepts were observed at the Polish site, *e.g.* CCS should 'reduce toxic waste' and 'reduce smog'. In all, results very tentatively suggested that public outreach in this community may have led to more uncertainty and questions. It would be interesting to investigate whether this is a common effect of public participation activities in a low-knowledge community and whether this observation disappears over time as more participation efforts are being performed. At the Scottish site, no misconceptions were reported. In fact, probably due to higher awareness and knowledge levels as well as ongoing CCS activities in the area, the survey data did not show any significant changes. Expectations of potential local CCS plans were rather different at the two sites. Polish expectations were mainly related to either positive or negative environmental impacts, but expected positive impacts were often misconceptions. The negative impact mentioned most often is that ' CO_2 will escape to the surface (and suffocate people)'. Other concerns were possible contamination of the ground water. Polish citizens also asked whether the technology is 'proven' and questioned the costs of CCS. At the Scottish site, expectations were mainly positive and related to economic impacts. The area was actually already used to offshore operations and CCS perceived as a logical, complementary activity to fishing, oil drilling and offshore renewables. There were some concerns amongst stakeholders about the interferences between different infrastructural projects, and amongst survey respondents about possible impact of CO_2 leakage on marine life. The local public required further information about the additional employment that might be created by CCS activities. Comparing the two studies, differences in the knowledge levels about the possible impacts of a CCS project and the proximity of the site to the local community appeared two key explanations for the differences observed in the perceptions and appreciations of the environmental risks of CCS which were most prominent in the Polish discussions, *versus* the economic benefits of CCS which were most prominent in the Scottish discussions. However, it should be noted that, despite environmental concerns, the Polish respondents were equally supportive of CCS in their area as the Scottish respondents.

Conditions for implementation of CCS projects – From these public engagement activities, conditions for implementation of CCS on (inter)national as well as local scale were derived. In both countries, acceptability of CCS was related to the implementation of other, preferred measures to combat climate change. The Scottish 'focus conference' group stated that CCS should be a short-term solution implemented alongside an exit strategy as to not divert attention from other options such as renewable energy. The government was not entirely trusted on viewing CCS as part of a long-term strategy for curbing climate change. The Polish 'focus conference' group feared that, while development of CCS in Poland could lead to a higher influence of Poland on the European policy for climate protection, alternatively it might turn Poland into a 'garbage dump' for European CO_2 emissions. In the end, most Polish 'focus conference' participants did not vote in favour of CCS because of the many uncertainties, little, if any, direct benefits to their region, and high costs of CCS. Participants argued that the role of national governments and the European government should be to develop a vision and to stimulate public involvement in decision-making regarding solutions to climate change. In contrast, Scottish participants discussed a possible role for Scotland as a main store of imported CO_2. Both groups however agreed that public should not just be informed about CCS, but also about alternative solutions to reduce CO_2 emissions into the atmosphere.

Conclusions – The research techniques for social site characterisation and public participation developed in SiteChar proved suitable for researching public perceptions of a complex issue such as CCS and to initiate local discussion. These results can be used in future project development, to start up and inform the process of information provision (*e.g.* draft a FAQ page, address misconceptions, and manage expectations) and public engagement (*e.g.* involve the right stakeholders and media). Some questions remain regarding the duration of public engagement effects, generalisation of findings from social site characterisation and public participation efforts to other sites, as well as applicability of the research methods and results to a real project setting.

3.4 SiteChar learning from site characterisation

The different steps of the characterisation workflow have been tested and outcomes illustrated on specific sites. They are related to the site characterisation activities as currently known. Additional characterisation activities might be appropriate or might be developed in the future. Key learnings have been derived and integrated in the SiteChar workflow. They are presented in SiteChar Deliverable D2.1 which is a public report available for download on the SiteChar website.

Fit-for-purpose and risk-based site characterisation – Site characterisation requires a fit-for-purpose workflow, dependent on the site-specific characteristics, the available data as well as the uncertainties and the risks to be investigated. Characterisation of a site for the purpose of obtaining a CO_2 storage permit is a risk-based process aiming at demonstrating safe and permanent storage. SiteChar recommends to drive site characterisation by risk and uncertainty assessment, aiming to anticipate, reduce and mitigate risks. Risk analysis should define the scope of the site characterisation work that iteratively determines and constrains risks and hopefully reduces their consequence and/or likelihood to acceptable levels. In this context, SiteChar experience has emphasised the need for a multidisciplinary expertise based on a close cooperation between disciplines sharing at the beginning of the project a common purpose for their activities, interdependencies, and during the investigation progress, any changes to the project concept or site design so as to provide an adequate qualification of all aspects of the storage site in line with regulatory requirements. Very close interaction between the static geological modelling, fluid flow modelling and coupled fluid flow and geomechanical/geochemical modelling should be planned for in the site characterisation work schedule. For instance, hydrodynamic modelling is sensitive to geological attribution; geomechanical modelling requires specific extension of the model and specific description of faults, *etc*. Therefore, communication to discuss input data that are required to be used in common between the activities as well as exchange of outputs from one modelling activity to another must be included in the plan of work. Similarly, all software to be used for static geological and hydrodynamic modelling of the storage site should be discussed at the outset of the characterisation. Compatibility and interoperability should be tested before decisions are taken regarding which modelling software to be licensed for use and staff assigned with appropriate modelling skills. Industry standard modelling tools seem preferable with respect to documentation of results to a regulatory body.

Geological assessment – Assessing the impact of CO_2 injection on the storage formation and potentially on the overall storage system requires the determination of the structural and stratigraphic setting. Geological assessment results in the construction of a 3D 'static' structural geological model or Earth model of the storage complex. This step is very time consuming, the duration depending on the availability of good-quality seismic data, corresponding borehole data and special core analyses. This step is very important since the geological model is the basis of the modelling of the storage behaviour. It has been the main element for the SiteChar site selection although some economic considerations should have been relevant, even at an early stage. SiteChar experience pointed out some uncertainties and risks factors related to the poor resolution of the seismic data that might ensure a sufficiently detailed representation of the storage complex. High quality data are needed in sufficient abundance and with a spatial distribution allowing characterisation of the various geological components of the storage site. Size and resolution of the model should fit the resolution of the available data. This influences the level of detail of the analysis that can be conducted in the characterisation. In addition it appears crucial to discuss at the early beginning of the site characterisation the extent of the model with other modellers so as to allow prediction of the CO_2 plume extent, assessment of geomechanical integrity, *etc*. More generally, a close interaction between geologists and engineers is recommended from the beginning of the project to share the purpose of the models, agree its characteristics and avoid possible software incompatibility. Last but not least, it has to be noted that assessing the quality of the model for the purpose of demonstrating a good understanding of the site is not an easy task. Relevant criteria are to be discussed amongst the whole group of experts that use this model with different objectives. It is thus advocated to consider, in addition to the selected model, multiple realisations (around four) of the model data, as is standard in oil and gas exploration, to take into account the uncertainties of some important features. Some sensitivity analyses were also conducted within SiteChar when necessary. It is recommended that the expert group building the static model is available at a later time for potential update of the model after hyrodynamic modelling and history matching production experiences.

Hydrodynamic modelling – Reservoir simulations of CO_2 injection and migration estimate several important features of storage behaviour, *e.g.* the injectivity, the storage capacity and the technical feasibility of the storage according to some maximum allowable reservoir pressure, possible CO_2 plume arrival to a spill point, *etc.* It also assesses the containment on the short term, *i.e.,* during injection operations till transfer of responsibility to a governmental authority, as well as in the long term including the fate and migration of CO_2 in the storage site. Displacement of formation fluids such as brine in an aquifer, of natural gas in depleted gas field or of crude in oil reservoirs was also important to predict. This step took a few months depending on the nature of the injection processes to be simulated and planned for and even longer time in the case update of the initial geological model is required to obtain a good history match. It was noted that modelling injection into depleted hydrocarbon reservoirs would benefit from previous modelling work, but that it might be difficult to gain access to production data from the operators. Modelling injection into virgin aquifers suffers from the lack of historical production data that are very useful to calibrate the models. Some information appears difficult to obtain with the necessary level of detail, in particular information associated with reservoir and basin heterogeneity which is a most influential parameter of model attribution, but also the distribution of petrophysical properties, fault behaviour and PVT conditions which require strong interaction amongst geologists and reservoir engineers. Sensitivity analyses using 'worst' and 'best' case scenarios have been used to address uncertainty due to lack of proper data, even if 'best' and 'worst' case scenarios should be considered with care since they might give a questionable idea of the storage site behaviour. Last but not least, SiteChar experience concluded that pressure management might be required in most CO_2 storages in deep saline aquifers. Brine treatment and disposal might be an issue for those storage aquifers that require pressure management by water production. Determining the maximum allowable pressure footprint on the surrounding areas is challenging; it is not fully described in the EC Storage Directive.

Geomechanical assessment – Predicting the mechanical response of reservoir to the increase of pressure resulting from the CO_2 injection is essential to ensure the storage integrity and forecast the pressure propagation over time. Geomechanical modelling requires strength properties of the storage site rocks and knowledge of the *in situ* stress state. It was pointed out the lack of good measurements of the *in situ* stress state so that initial stress conditions were to be derived from literature. Information on fault properties appeared as a critical limitation for the characterisation of CO_2 geological storage sites and the assessment of their integrity. Understanding fault behaviour during CO_2 injection thus requires additional activities, such as sensitivity analyses or cautious ‘worst’ and ‘best’ case scenarios, measurements of stress and injection tests. Overburden properties are also often not sufficiently known since they have not been investigated by the oil and gas industry. Pressure history data indicating pressure communication within a regionally extensive sandstone could inform the likely sealing properties of faults and boundaries, but such information might not be publicly available even for strata that are well known from hydrocarbon production although such data may exist held in confidence by hydrocarbon field operators.

***Geochemical assessment* –** Once dissolved in brine, CO_2 can induce geochemical processes such as dissolution and precipitation of rock-forming minerals, which are key trapping mechanisms and are essential to understand long-term storage activities, but which may also affect the reservoir and/or the cap rock integrity. The mineralogy of the host strata is a key input to the geochemical modelling. The more detailed the compositional information is obtained by core analysis, the more appropriate the predicted changes associated with CO_2 injection will be. Ideally, the mineralogy data used should be derived from core from or in the immediate vicinity of the proposed injection well to minimise the possibility of any lateral changes in composition. When input data were not available, SiteChar made use of assumed values or appropriate analogue data taken from published literature or previous work. The impact of CO_2 injection on the chemical character of existing well infrastructure and well cements used at the proposed injection site should also be modelled but proper information on well cement and other well material were most often not available within SiteChar. In addition, it was pointed out the need for further development of modelling software able to predict reactions in oil-, gas- and brine-bearing strata.

***Well integrity assessment* –** Potential leakage pathways via existing or abandoned wells have been evaluated as the highest risk of leakage for all the SiteChar sites comprising existing wells. Assessing well integrity and future use or abandonment of existing wells is a time consuming activity, the effort being of course highly dependent on the number of wells to be analysed and the availability of appropriate data. In particular old abandoned hydrocarbon exploration wells appeared difficult to assess because of missing data and proper abandonment documentation. Availability of proper data (*e.g.* status of cementation, well casing) is a major issue, in particular for depleted hydrocarbon fields that are drilled with a large number of wells, so that there is most often a need for cautious ‘worst case’ scenarios to supplement as far as possible the lack of data. It was also concluded that *in situ* observations in wells should be required in the case of a real project. Such operations being very expensive, SiteChar recommends to estimate the cost and the timing of the operations as early as possible. Lastly a dedicated risk assessment workshop was found very useful to evaluate future options for the wells.

***Monitoring planning* –** It is most likely that some uncertainties and residual risks will still remain following a detailed site characterisation. The main objectives of the monitoring plan are to verify the conformity of the injected CO_2 with prediction, provide an early warning in the case the CO_2 migrates so as to allow implementation of remedial actions, and provide relevant data that would be acquired all along the phases of the project to refine and update the models when necessary. Monitoring planning has to be fit-for-purpose addressing areas of highest residual risk. Setting up a comprehensive monitoring plan requires identification of all risks from the risk assessment and simulations of different injection scenarios from the hydrodynamic model. Baseline studies require a lot of efforts but they are essential to secure that enough data are collected. SiteChar pointed out the need for feasibility studies of all the monitoring tools deployed to demonstrate storage site performance and ensure efficacy and cost-benefit for their use at the storage site. It would be particularly important to understand the occurrence and consequence of ‘extreme events’, *e.g.* sudden release of CO_2 accumulated under snow that might happen in spring when ice melts and conditions for their occurrence. SiteChar recommends that data are open to the public and actively disseminated, both during the baseline activities and during the monitoring phase to inform local stakeholders on what type of data have been and are to be acquired and what range of values are typically encountered in the investigated area. This could be a bridge for dialogue with the local stakeholders, both prior to and during the injection phases.

Economic assessment – A comparative economic evaluation of the three offshore sites in the UK sector of the North Sea off Scotland, the Southern Adriatic Sea and the Norwegian Sea and the onshore site in Denmark has been carried out to analyse the cost of each phase of the storage projects, from exploration and site characterisation, to site development, drilling and injection, up to monitoring and site abandonment. The aim of the economic assessment conducted in SiteChar was to understand the critical and most influential parameters in the economic assessment. The variability of the sites and of their characterisation allowed for an interesting range for comparison. The wide range of costs obtained (from 3 €/tonne CO_2 onshore to 29 €/tonne CO_2 offshore) confirms that there is no meaningful average cost for CO_2 storage. The structure of the cost is very heterogeneous and the equivalent storage cost very site dependent. The main difference in the structure of the cost is attributable to the site location (onshore/offshore), the amount of CO_2 injected, the well injectivity rate, the number of CO_2 injection and water production wells, and the necessity or not to produce and treat water. Moreover, monitoring plans include very different types of survey from one site to another, with permanent and non-permanent systems, used in different ways and for different frequencies of monitoring. The main uncertainties in the costs did not seem to be linked to data themselves but rather to the choice of economic parameters and to the technical choice of operations. Their impact has been addressed by sensitivity analyses. It was pointed out that questions about the real lifetime of a CO_2 storage project still have to be answered by policy makers, *e.g.* what should be the abandon phase and the associated cost and what is the real value of the liability transfer after twenty years of storage.

Public outreach – Social site characterisation is crucially important; all technical site characterisation activities must be tailored to the local circumstances when developing a project. This requires identification of relevant stakeholders and factors that drive public perception regarding CCS as well as the adequate media to communicate with the public. Information should be balanced, coming from different sources and including possible uncertainty and risks. Negative and positive expectations should be openly discussed, taking into account low knowledge levels and possible misperceptions about CCS, CO_2 and climate change. SiteChar recommends combination of multiple research methods (*e.g.* surveys, ‘focus conferences’) in order to obtain the best results. The timing of each step is also important: it is recommended to begin with interviews to get acquainted with the area and obtain background information, quantify these findings with a survey, align all public activities such as focus conferences and finally organise information meetings to increase effectiveness and involvement of the local public.

3.5 Conclusions and Recommendations

By demonstrating the level of geological characterisation needed to meet regulatory requirements, in particular the EC Storage Directive, SiteChar has assessed some of the key steps required to make timely effective large-scale implementation of CO_2 storage in Europe. The development of ‘dry-run’ storage permit applications at two credible CO_2 storage sites allowed identification of effective approaches to site characterisation, enabling robust and defensible permit applications to be developed by operators. The review of these applications and the lessons learnt are expected to help regulatory authorities to identify the necessary levels of evidence required to assess the safety, containment and capacity of a potential storage site. A methodology and best practice for the preparation of storage permit applications have been developed, incorporating all available technical and economic data, as well as some social aspects. Recommendations were derived to enable operators to address key issues for cost efficient and effective storage permit applications. Recommendations were also derived to improve and clarify the EC Storage Directive on a number of topics including the benefits of establishing permit performance conditions, the circumstances under which permits might be revised, the role of competent authorities in evaluating the potential impacts of storage projects on other future uses of the underground and the challenges of planning all details of the operation prior to final investment decisions and subsequent site testing. They are presented in SiteChar Deliverable D2.4 which is a public report available for download on the SiteChar website.

Focused site characterisation – The research conducted in SiteChar confirms that appropriate site characterisation provides a route to successful storage operations. Key for success is to ensure that the characterisation activities are fit-for-purpose and focus on reducing uncertainty and risk for the specific site and the specific CO_2 storage project. This requires the competent authority and the operator to share a common understanding of the site and the storage project. Site characterisation should demonstrate that the site has sufficient capacity to accept the expected CO_2 volume, sufficient injectivity to receive the expected rate of supplied CO_2, and sufficient containment to permanently store the injected CO_2. Consequently, it is recommended that the priorities addressed during site characterisation are driven by risk and uncertainty assessment, aiming to anticipate, reduce and mitigate risks and identify objectives for subsequent storage performance monitoring.

Challenge in the definition of the storage complex – Practical approaches to defining the storage complex are required and have been developed. SiteChar derived recommendations to improve and clarify the EC Storage Directive on a number of topics including the benefits of establishing 'Permit Performance Conditions', the circumstances under which permits might be revised, the role of competent authorities in evaluating the potential impacts of storage projects on other future uses of the subsurface and the challenges of planning all details of the operation prior to final investment decisions and subsequent site testing.

Uncertainties and site performance – Managing uncertainty and conveying the level of confidence accurately without undermining the safety case require specific attention. Indeed all predictions of site performance will carry a level of confidence and uncertainty so that it will be important for competent authorities and operators to agree on the level of acceptable uncertainty as well as on a plan for uncertainty reduction during site operation. This will be supported by a baseline site characterisation and an appropriate monitoring programme to detect any possible irregularities. It was pointed out that definition of acceptance criteria is the key to determine what is good enough to gain a storage permit; such criteria should allow both operator and regulator to demonstrate adequate site performance both during the operational and closure phases and should provide a basis for the design of the geological monitoring programme and the corrective measures plan.

Site performance – A significant aspect of site characterisation activities should be establishing agreement on the level of adequate evidence needed to demonstrate permanent safe containment and enable the transfer of the site to the State. This transfer is expected to be planned from the beginning and prepared for during the process. If dialogue between the competent authority and the operator is ongoing and if the understanding of the site is appropriate, there is no reason for the site not to be transferred to the State at the legitimate end of the storage operation. It was pointed out that both operators and competent authorities will need certainty on the metrics by which the site performance will be assessed and the safe and permanent containment demonstrated.

Outlook – Governments and national authorities should play an active role to make CO_2 storage projects part of a local political approach regarding energy as well as use of the subsurface. In particular, it was noted that, if assessing interactions with other users is a key consideration for regulators, this might be very challenging for operators since such an assessment requires an overview of any future uses of the underground interactions. Management of pore space is also a strategic issue that could require an evaluation by both operators and relevant authorities of the efficient use of the pore space in the selection and operation of sites. SiteChar also concludes there is a need for demonstration projects to fully test the regulatory requirements and investigate cost reduction at a much larger scale.

4 Potential impacts and main dissemination activities and exploitation results

4.1 Potential impact

SiteChar provided an unique opportunity to test and improve the process for issuing storage permits in the current period where Carbone Capture and Storage (CCS) is experiencing a number of difficulties, regarding financing issues, implementation of a regulatory framework, securing a high enough CO_2 price that would make CCS a viable option. Lessons learnt from the SiteChar project and resulting transferable knowledge inform assessment and permitting needs for CO_2 geological storage sites in Europe. A methodology and best practice have been developed for the preparation of storage permit applications, incorporating all available technical and economic data, as well as some social aspects. Recommendations were derived to enable operators to address key issues for cost efficient and effective storage permit applications. To some extent, SiteChar has thus been able to supplement the lack of industrial demonstration projects by delivering both technical and social-related results that should enable optimisation and better shape of future CCS industrial projects. Crucially, the knowledge gained should help operators and researchers to conduct a proper assessment of potential CO_2 storage sites aiming at demonstrating safe and permanent storage. Review of the ‘dry-run’ storage permit applications against the requirements in the EC Storage Directive, and the associated Guidance Documents as well as, for the UK site, the UK-specific guidance documents is expected to feed into the development of regulatory frameworks for the CO_2 geological storage which is considered as a critical component in the portfolio of low-carbon energy technologies.

SiteChar has delivered a robust methodology for storage site characterisation in an European geological and regulatory context, through technical innovative developments and tests on onshore and offshore open deep saline aquifer traps, structurally closed deep saline aquifers and depleted hydrocarbon reservoirs that could be used in the near term for CO_2 geological storage. Two levels of characterisation have been investigated within SiteChar. At the Polish Załęcze and Żuchlów gas fields, the Norwegian Trøndelag platform and the Southern Adriatic Sea site, the characterisation has been performed from the early phases of the workflow aiming to investigate new prospective areas for CO_2 geological storage. At the offshore UK North Sea multi-store site and the onshore Vedsted aquifer site in Denmark, a full-chain storage site characterisation suitable for a ‘dry-run’ storage permit application has been performed. These two contrasting storage sites are representative of two realistic storage options, though neither currently being considered as near-term candidates. Even though the offshore UK North Sea site had been identified from previous reviews of UK northern North Sea storage targets, it was a theoretical study designed to test a credible scenario for CO_2 storage extending storage in a hydrocarbon field to large-scale CO_2 storage in a saline aquifer which would be commercially viable. The second case study extended existing investigations at the Danish Vedsted site, a deep onshore aquifer, processed by Vattenfall till late 2011 to be an industrial scale demo project. At these two sites, ‘dry-run’ storage permit applications have been produced and evaluated by a group of independent international experts and made available to the Scottish Government for discussion with the UK CCS Regulatory Group. The results and knowledge obtained from the detailed characterisation at these sites are thus expected to increase the confidence for successful CO_2 geological storage in Europe.

SiteChar has supplied a methodological guide adapted to specific European geological contexts for use by storage operators and regulatory bodies, including a detailed estimation of storage capacity and injectivity, modelling of hydrodynamic reservoir behaviour, and safety aspects including requirements for measurement, monitoring and verification of the stored CO_2. The research focused on the latter stages of the characterisation in order to achieve a detailed analysis of the economic viability of storage in a subsurface reservoir. In particular, it was important to provide a better understanding of the aquifer geometry at the basin scale in order to estimate a realistic distribution of far-field overpressure perturbations. Advanced hydrodynamic modelling of the storage sites has been performed accounting for fluid-rock interaction and mechanical structure response including in particular the simulation of the faults behaviour and the propagation of the pressure front. Risk assessment and risk reduction was a key driver of the characterisation activities and resulted in the design of monitoring and remediation plans as required to reach the final stage of permitting. The SiteChar workflow is a consolidated and validated site characterisation workflow that is aligned with the EC Storage Directive, Annex I. It provides a description of all elements of a site characterisation study, as well as guidance to streamline the site characterisation process and ensure that it covers the aspects specified in the EC Storage Directive. It has been tested and validated at a range of five sites representative of European geological contexts. This workflow should help to speed up the characterisation of new CO_2 geological storage sites.

Public awareness has been addressed at an offshore site and an onshore site. Results provide insight on the way local CCS plans may be perceived by the local stakeholders and how public opinion can be reliably assessed at an early stage of a project without raising unnecessary concerns. The 'focus conference' approach tested in SiteChar appears suitable for raising public awareness and assisting public opinion formation about complex issues such as CCS. It can be used to initiate local discussion and planning processes together with the local community in a balanced and informed way. For the site offshore Scotland, results of the public outreach activities were integrated in the 'dry-run' storage permit application, allowing conclusions to be drawn on best practice considering both the technical quality and the related public consultation. These methods and results can be used in future project development to start up and inform the process of information provision and public engagement.

Best practice and guidelines for site characterisation as part of large-scale deployment of CCS in Europe have been delivered in partnership with industry and regulatory agencies. These guidelines synthesise the experiences acquired on the case studies into recommendations for storage permitting, including regulatory, technical and public consultation aspects. They also identify issues met on specific elements of the workflow that could limit this deployment and provide a breakdown of the scientific, technical and social bottlenecks requiring further investigations in order to achieve readiness for large-scale implementation of CO_2 storage in Europe. A short review of the EC Storage Directive is also presented so as to evaluate its realistic application. Finally SiteChar provides legal administrations information, guidelines and real putative European CO_2 geological storage sites that will allow to discuss international or national legislation and to put on the bases for a public acceptance of CO_2 storage in deep geological formations. To this extent, the SiteChar experience is expected to support the implementation of the European Industrial Initiative on CCS mentioned in the SET Plan.

4.2 Added value of a European approach

The SiteChar consortium integrated major entities in the field of CCS, including research institutes, academics, oil and gas companies, power companies and public authorities providing the wide and multidisciplinary expertise required to cover all the steps for the identification and characterisation of sites for CO_2 geological storage and face the challenges of large-scale CCS development.

Several of the partners have been and are strongly involved in previous and ongoing European CCS projects. This ensured that the work performed in SiteChar has been complementary to ongoing CCS programme focusing on filling in the missing parts of some CO_2 value chain in order to facilitate large scale CCS within a short term. Beyond European initiatives, SiteChar partners took and still take part in CCS developments in their own activities through national funding projects or business. The partnership also includes partners that are actively involved in global forums and cooperation actions within CCS, such as ZEP, EERA and CO_2GeoNet. In addition, two external partners, Veolia Environnement and Gassnova thoroughly followed the SiteChar project.

If CCS becomes deployed on a wider scale, several storage project developers, both as partners in SiteChar and beyond, will be required to develop storage projects across Europe which will demand a consistent approach to site characterisation. The methodologies, knowledge and outputs developed in SiteChar will have wide generic applicability for all Member States considering CO_2 geological storage. Consolidation of the site characterisation workflow is indeed a key issue for the European industry. The sites studied in SiteChar, *i.e.,* offshore multi-store site in UK North Sea, onshore aquifer in Denmark, onshore depleted hydrocarbon fields in Poland, offshore aquifer Mid-Norway and offshore aquifer in the Southern Adriatic Sea, are evident examples of what is needed for the deployment of the CCS chain by 2020 in Europe. Relying on the assessment of a portfolio of potential sites for CO_2 geological storage as well as generic deliverables, SiteChar should thus contribute to faster implementation of CCS for European industry. In addition, expertise and technologies developed within SiteChar are expected to give European industry a significant advantage for exporting worldwide services and technology for engineering design and economical evaluation for CO_2 storage systems.

4.3 Dissemination of the project results

SiteChar has been specifically designed to ensure maximum effective dissemination at a range of levels and to a range of key stakeholder groups. The consortium includes the full CCS chain stakeholders from generators through oil and gas companies to regulators. A specific work package was dedicated to public outreach activities. The two 'dry-run' storage permit applications developed within SiteChar required consultation with a number of stakeholder groups, including regulators, statutory consultees, trade bodies, local authorities and planning departments, local populations and their representatives. A specific work package was dedicated to ensure the overall technical coordination of the project as well as to share and analyse the key results. Both the generic methodologies and results from topical activities were actively disseminated all along the project. This specificity of the SiteChar project led to a better understanding on how CCS can be implemented and has been reported as guidelines for future CCS projects.

The SiteChar secure web site was used as a first tool to disseminate the information at the different levels. Public deliverables were made available and summary of restricted and confidential deliverables were produced.

The SiteChar project promoted results and approaches through the existing networks (*e.g.* ZEP Regulation and Policy Task Force, CO_2GeoNet). SiteChar was presented at the CO_2NET Annual seminar in May 2011 and the CO_2GeoNet Open Forum in April 2012 and April 2013. Several partners were and are very active in some of these networks and promoted SiteChar results. In addition, communication with other CCS projects or initiatives ensured a good communication (in and out) with relevant projects and activities in Europe. Exchanges were arranged with projects related to the CCS topic. In particular, the First SiteChar Workshop for Stakeholders was organised the day following the final conference of CO_2ReMove (1^{st} March 2012) and at the same place (IFPEN, France). Similarly the SiteChar Closing conference was organised the day before the RISCS Closing Conference (28^{th} November 2013) and at the same place (IFPEN, France). Such an organisation allowed participants to easily attend both events and share the results of both projects. In addition, the First SiteChar Workshop provided the opportunity to EU projects CO_2CARE, RISCS, QICS, Ultimate CO_2 to present their project and the results obtained so far. A representative of CO_2CARE was invited at the Third SiteChar Workshop for Stakeholders to present the state of the art regarding well integrity. Similarly SiteChar was presented at the CO_2CARE workshop on 26^{th} March 2012 and at the CO_2CARE Closing Conference on 4^{th} November 2013. Posters presenting the SiteChar project and results were prepared at the CO_2ReMove Closing Conference in March 2012 and the CO_2CARE Closing Conference in November 2013.

Three workshops were organised during the course of the project focused on SiteChar key topics. The first one (1^{st} March 2012, IFPEN, France) was dedicated to the SiteChar project philosophy and workflow to characterise a potential CO_2 geological storage site up to the final stage of storage permitting. The second one (11^{th} December 2012, Imperial, UK) was dedicated to public awareness and acceptability of CCS technology. The third one (24^{th} September 2013, TNO, The Netherlands) was dedicated to the SiteChar workflow for site characterisation specifically relevant to CCS operators, regulators and researchers. These three workshops attracted significant interest from the wider community of stakeholders.

The SiteChar Closing Conference (28^{th} November 2013, IFPEN, France) was hailed as a success having gathered almost 70 participants from the wider community of stakeholders, *i.e.,* researchers, industry, regulators from Australia, Belgium, Denmak, Germany, Italy, Norway, Poland, Spain, The Netherlands, UK, USA. The conference was dedicated to the learnings of the project in the purpose of storage permitting with a morning session dedicated to site characterisation for storage permitting and an afternoon session to the SiteChar workflow for integrated and accountable site characterisation. Outcomes and guidelines were illustrated at the five putative European storage sites studied in SiteChar. The SiteChar Closing Conference provided in addition an opportunity to discuss necessary activities to meet storage permit requirements.

SiteChar results were published in scientific publications and journals with peer-review and presented in international conferences. Three papers have already been published in Energy Procedia. A special issue of the OGST journal dedicated to SiteChar is in preparation for publication early 2015. Ten papers have already been submitted and five are in preparation or finalisation. Twenty-seven presentations of the project or of specific activities have been given at international conferences, either as oral presentations or as posters, five have already been accepted to forthcoming conferences either as oral presentations or as posters and two other ones submitted.

The general public has been addressed through public outreach activities. A specific work package was dedicated to advance public awareness. Thorough public participation activities were conducted at two prospective CCS sites: the onshore Polish site and the offshore Scottish site. The SiteChar website supported public outreach activities by providing generic and site-specific information to the public through public sections both in English and in Polish.

Last but not the least level of communication was towards the policy makers. The work on establishing best practice in the permitting process was particularly important in this regard. Discussions with regulators and policymakers with responsibility for storage in a several European countries were arranged through specific meetings in addition to the three workshops for stakeholders and the SiteChar Closing Conference.

4.4 Exploitation of the project results

The SiteChar consortium had the whole competence to develop and promote the research activities and the methodologies required for CO_2 geological characterisation and assessment of long-term storage site behaviour. It has also the capability to exploit the knowledge resulting from this project, including the results of the site-specific activities covered by the SiteChar industrial partners who range from site operators to end users (power companies). This methodology and its various developments and improvements during the project time-life was also an essential tool for the discussion with regulatory bodies at national and European levels. For that purpose a specific committee, the Advisory Board on Regulation including researchers, industry representative and regulators, was established.

The results produced by SiteChar are of four kinds: a generic site characterisation workflow, general guidelines for large-scale deployment of CCS in Europe, including best practice guidance on storage permitting with particular reference to site characterisation aspects, innovative tools and methods dedicated to deep saline aquifer qualification based on data made available by national and industrial projects and resulting studies done in SiteChar. In the site applications, some specific and innovative tools and methods were developed and validated. On the UK site, methodologies and modelling capabilities for considering multi-store injection scenarios, including pressure management, have been developed and will help research partners, industry and regulators to better understand CO_2 storage in these situations. On the Danish site, an innovative co-modelling approach has been developed for the fluid flow simulation of site models respecting hydrodynamic boundary conditions given by the surrounding regional basin-scale model behaviour. An incremental development is proposed to secure and improve future operations and extrapolations of site performance. On the Polish site, a methodology for analysing the impact of gas production processes on the long-term safety of CO_2 storage was developed. Long-term reactivity was also modelled. On the Norwegian site, several basin modelling tools were tested and further developed for CO_2 migration modelling with special focus on possible leakage along faults. On the Italian site, a robust methodology was developed for CO_2 storage site characterisation in carbonate formations. Coupled fluid flow simulation and geomechanics investigated the effect that a naturally fractured reservoir may have on CO_2 flow during CO_2 storage. These methodologies will be used, tested and developed further by all partners of the SiteChar project and in particular the industrial partners as they are involved in ongoing and future CO_2 storage operations and/or technology development.

IFPEN – The research activities performed in SiteChar has allowed to test and improved both IFPEN methodologies and software for characterising and simulating the site behaviour. Application of the whole characterisation workflow on the different sites which are representative of potential options for CO_2 storage led to significant learning that will be precious for IFPEN future activities. The cooperative work achieved in

SiteChar has reinforced internal IFPEN knowledge on site characterisation and in particular on the coupling of the different modelling software. This work has also highlighted some missing crucial data and some improvements to be achieved which will be useful for future projects. The results obtained and the knowledge gained in the SiteChar project have been widely disseminated during the SiteChar project. A number of forthcoming dissemination activities (publications, communications to international conferences) are planned. As coordinator as well as partner of the SiteChar project, IFPEN has had important and very fruitful exchanges with the whole community of stakeholders which are a strong basis for ongoing fruitful collaborations in wider projects.

TNO – The site characterisation workflow formed a logical extension of earlier work done by TNO. The work achieved in SiteChar has provided a firmer basis for the knowledge in TNO on site characterisation. TNO will use this in its role in the ISO working group on standards for CO_2 storage. Through the ISO process, the results from the SiteChar project will find their way into worldwide standards.

SINTEF-PR – SINTEF-PR will use the results from SiteChar in ongoing research project like the "NORDICCS – Nordic CCS Competence Centre". The main objective of NORDICCS is to boost the deployment of carbon capture and storage (CCS) in the Nordic countries by creating a durable network of excellence integrating R&D capacities and relevant industry.

GFZ – The work carried out by GFZ contributed to the GFZ expertise in numerical modelling by allowing to validate new numerical model coupling concepts between scientific and commercial numerical simulators against purely commercial implementations. The generated knowledge and validated model coupling schemes can be directly applied in upcoming national and international R&D projects. Furthermore, GFZ was able to verify applicability of the developed model coupling schemes regarding two different study areas and CO_2 storage scenarios in two work packages. Hence, resulting model developments are available for application in further research activities and scientific publications.

NERC-BGS – Knowledge of the geology of the storage site strata, that are host to two proposed UK demonstrator CCS projects, has been greatly enhanced by the interpretation of geological data and detailed research investigations for the UK offshore site. Discussion with a prospective CCS operator through the SiteChar Advisory Board has afforded a very valuable understanding of the perspective of a storage site operator. The static geological model and understanding of the attribution method and its outcome, in terms of storage site performance, will be taken forward in additional CCS research projects by BGS and the Scottish Government in Scotland. Existing expertise in the merging of static geological models has been enhanced by the SiteChar experience. Methods to derive 'facies' logs from digital well data and population of the attributed cellular model using stochastic methods constrained by core sample measurements were both established in SiteChar. The application and process of risk assessment-led site characterisation has been a significant learning from the SiteChar project in NERC-BGS. Risk assessment-led site characterisation has already been applied to a research project to determine the interaction and cumulative effect of two storage sites in the Captain Sandstone to derive generic learning relevant to any multi-user storage site, by the Scottish Government and industry-funded CO_2MultiStore project *www.sccs.org.uk/expertise/CO_2MultiStoreAllEnergy2013.pdf*. Presentation of a 'dry-run' storage permit application has highlighted the objective of site characterisation to meet the requirements of the EC Storage Directive both in terms of the activities needed and the outputs required from site characterisation. This is invaluable to researchers to understand what determines needed technical investigations to meet the outputs required for a storage permit application. The storage permit application for the SiteChar UK storage site has been provided to the Scottish Government for dissemination to the UK CCS regulatory group, which includes the UK national bodies for leasing of storage sites and offshore environmental protection and Scottish regulators, for their information, comment and use. Agreement of the SiteChar consortium to the proposal by NERC-BGS to change the nature of the reported technical site characterisation deliverables from 'restricted' to 'public' will now enable NERC-BGS to disseminate the research for the UK site much more widely in presentations, publications and future collaborative research.

GEUS – The issue with operational pressure footprint on the surroundings and potential pressure management by water production will be continued in future projects on investigating the synergy benefits in combining CCS with low enthalpy geothermal energy utilisation in Denmark. Further the produced 'dry-run' permit application is a base for dialogue with the Danish regulatory bodies for potentially developing CCS in Denmark after 2020.

AGH – The experience gained within SiteChar (modelling, interpretation of results, laboratory tests) will be helpful in future projects. During the work, cooperation with SiteChar partners, such as exchange of experience in the construction of numerical models, was also essential to increase knowledge. Research activities also highlighted the lack of some data that may be relevant and should be considered in future projects.

UfU - UfU further developed its skills and experience in conducting really participative forms of communication with stakeholder and the general public and the assessment of data collected during the communication process. Some communication tools were re-designed to adjust them to the specific task and the specific setting in Poland. On the other hand, UfU, which is both a scientific institute and an environmental NGO, had to develop a method to handle an issue like CCS that is under dispute in the 'environmental scene' in a way that is both productive for the project and acceptable within the institute and beyond. This gives UfU the opportunity to handle similar issues and projects in the future.

ECN – The core strength of ECN's social research group is developing innovative ways for understanding and working with the 'human factor' in energy technology development and deployment. The work performed in SiteChar has reinforced and expanded ECN's experience with formats for organising informed public dialogues as well as surveying techniques for obtaining reliable measurements of uninformed opinions. These lessons feed directly into other ongoing and new projects. To maximise further utilisation of the data and exposure to the outcomes, a 'Memorandum of Understanding on Public Perceptions Research' between the FP7 ECO_2 project and the SiteChar project has been signed by ECN, GEOMAR, and the University of Edinburgh (UEDIN), which enables UEDIN to use the relations they built and the data they collected within the SiteChar project to feed their research activities in ECO_2.

Imperial – Imperial College has been involved in reservoir simulation of CO_2 injection and modelling of coupled geomechanical response of the storage system for three sites considered in the SiteChar project. The knowhow and experiences gained in seamless coupling of two software, namely ECLIPSE for fluid flow and VISAGE for geomechanics modelling, will be further exploited in Imperial current projects for the Crown Estate in the UK, assisting them in evaluating, valuing and licensing storage sites to the industry within the UK sector.

OGS – The characterisation of the Italian site had the objective of tackling some particular issues related to the storage in carbonate formations which is the potential reservoir identified in the Southern Adriatic offshore. The study performed within the SiteChar project highlighted the uncertainties and the risks associated to the application of CCS in the investigated area. A methodological approach was proposed, to be considered for future investigations in the Southern Adriatic area and, at the same time, it represents a case history for any storage project in carbonate reservoirs that would support scientists and decision makers involved in a potential feasibility study in similar carbonate reservoir formations. The experience gained within SiteChar will be of great benefit for future projects and will give OGS the opportunity to increase its expertise in the characterisation of carbonate formation and in the knowledge of the potentiality for CO_2 storage in the Southern Adriatic area. The results were already included in the characterisation workflow prepared within SiteChar project. Moreover, OGS plans to participate to national and international meetings and to produce papers to be published on technical journals of international level to disseminate results gained in the characterisation.

UniRoma1-CERI – Exploitation and dissemination are focused in four areas. Firstly, the near surface gas geochemistry work conducted by UniRoma1-CERI at the Hobe research centre at Voulund, central Denmark (proxy for the Vedsted site) has extended UniRoma1-CERI knowledge of baseline gas values and distributions in a northern European marine climate. The observed influence of seasonal and land-use variations on the collected data will be used in future research and within dissemination work regarding the importance of baseline studies for potential CCS sites, both in terms of a framework in which monitoring results can be put and to educate the local stakeholders of the natural, near-surface, variability of the site. Secondly, the continued development work performed on the UniRoma1-CERI CO_2 probes within SiteChar has improved their capabilities and will allow to expand their use and exploitation in future research projects. Thirdly, the collaboration between UniRoma1-CERI and GEUS has been extended beyond the life-time of the SiteChar project with the deployment of three additional UniRoma1 CO_2 monitoring probes at the Hobe test site at the end of the project for an estimated period of one year. This has been done to extend the results obtained during the SiteChar project by including monitoring of natural variability over four complete seasons. The obtained data will help UniRoma1-CERI in developing a protocol for the combined use of discontinuous and continuous monitoring methods that will ensure optimal spatial and temporal baseline definition of a studied site. Lastly, the work done by UniRoma1-CERI to disseminate the SiteChar project's activities has led to some important discussions, particularly during the third stakeholder workshop, which form the basis for further exchange amongst the stakeholders involved. The report produced at the end of the project for a wider audience will be printed and distributed at CO_2GeoNet Open Forum 2014 to encourage stakeholders to use both the printable and the online version to communicate with the public and disseminate the key concepts of site characterisation. The report will also be translated in Italian for use in the national context.

Vattenfall – The SiteChar project gave the opportunity to Vattenfall to gain further knowledge from data acquired in the demo phase of Vattenfall onshore CCS Demo Denmark project related to the Nordjyllandsværket northern Denmark. The work achieved has demonstrated the challenges in characterisation of an onshore site with sparse data coverage and defined the minimum criteria for submitting storage applications through the 'dry-run' permit work performed. Vattenfall will in the ongoing work in CCS draw on the experience of the SiteChar project.

ENEL – The work performed within SiteChar project has confirmed and structured the site characterisation process. Moreover it has increased the knowledge about the Southern Adriatic sea. This work has also highlighted some peculiarities related to carbonate reservoirs which will be useful for future projects.

Statoil – Statoil is operator of two CO_2 storages at the Sleipner and Snøhvit fields offshore Norway, and has ambitions to utilise the SiteChar workflows to become operator for new CO_2 storages in the future.

SG – The Scottish Government believes that the information gathered in SiteChar's outreach exercises to communities in Poland and in Scotland, provides important and very useful insights into public perceptions and public awareness of CCS. Likewise the geotechnical information and modelling data generated through the SiteChar project will be of great interest to Government's, public bodies, regulators and industry. The Scottish Government intends to use the outputs and findings from the SiteChar project for dissemination though it's Thermal Generation & CCS Industry Leadership Group (TG&CCS-ILG) – this group meets quarterly and is attended by key power and energy industry representatives most of whom will be involved in CCS power generation and CCS supply chain activity as the CCS industry develops. This group is co-chaired by the Scottish Government's Energy Minister and Graham Sweeney (Chairman of ZEP). The TG&CCS-ILG is a sub-group which reports to the Scottish Government First Ministers Energy Advisory Board. Additionally the findings of Sitechar will be disseminated throughout the Scottish Government's Energy & Climate Change Directorate through presentations by lead officials involved in the project. The knowledge gained from SiteChar will be used to add to and bolster our understanding of the storage capacity of the North Sea which is viewed as a National Asset.

5 Address of project public website and relevant contact details

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