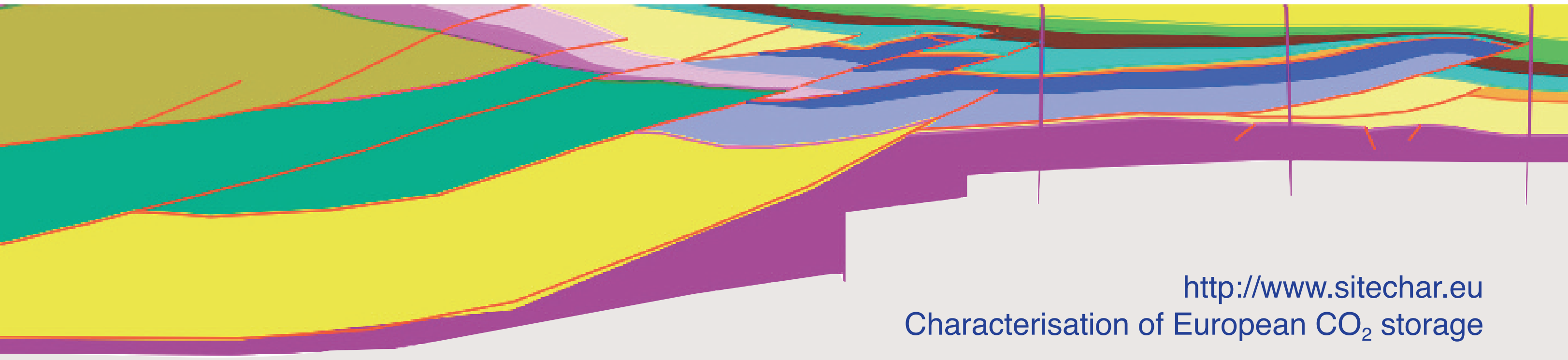
# Choosing good sites for storing $CO_2$ underground

## Research highlights from the EU FP7 "SiteChar" Project



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Characterisation of European $CO_2$ storage

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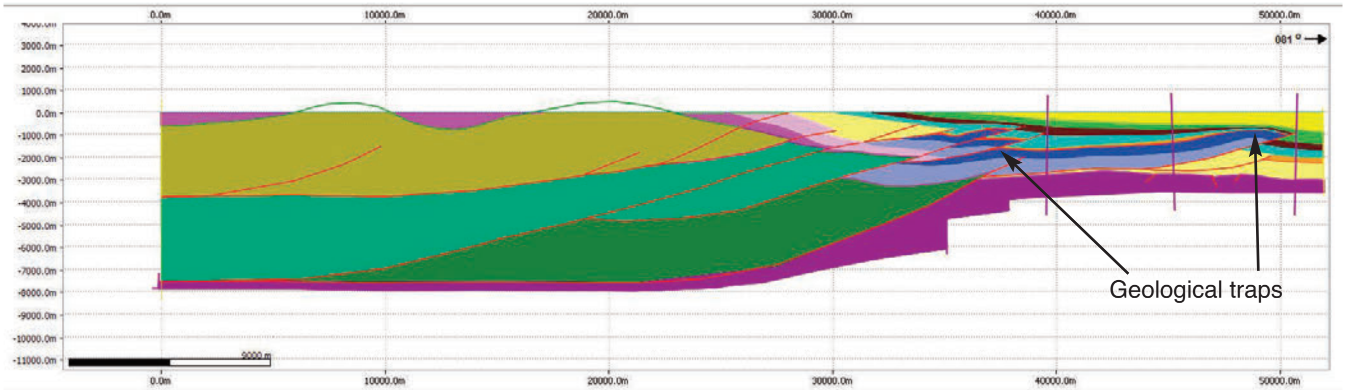

Front cover: geological cross section of the northern Apennines from Ascoli Piceno to the Adriatic Sea, showing the spatial distribution of different rock types and structures down to a depth of about 8000 m (Bigi et al., 2010) Some geological traps can be seen; these are the kind of geological features that can trap the injected $CO_2$.

# CHOOSING GOOD SITES FOR STORING $CO_2$ UNDERGROUND

## RESEARCH HIGHLIGHTS FROM THE EU FP7 "SITECHAR" PROJECT

*Fig.1 - SiteChar Closing Conference participants, November 2013*

## ACKNOWLEDGMENTS

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## REFERENCE

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IFP Energies nouvelles

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## Focus on:

# CHOOSING GOOD SITES FOR STORING $CO_2$ UNDERGROUND

## RESEARCH HIGHLIGHTS FROM THE EU FP7 "SITECHAR" PROJECT

# PART 1. THE IMPLEMENTATION OF $CO_2$ GEOLOGICAL STORAGE IN EUROPE

## 1.1. THE ROLE OF CCS FOR REDUCING $CO_2$ EMISSIONS

Carbon dioxide Capture and Storage (CCS) has been identified by the European authorities as one of the technologies that we need to implement to reduce $CO_2$ emissions: "Various forms of low carbon energy sources, their supporting systems and infrastructure, including smart grids, passive housing, carbon capture and storage, advanced industrial processes and electrification of transport (including energy storage technologies) are key components which are starting to form the backbone of efficient, low carbon energy and transport systems after 2020." (A Roadmap for moving to a competitive low carbon economy in 2050). This approach has been confirmed, with regard to CCS, by the European Parliament resolution on CCS of 14 January 2014.

According to the International Energy Agency CCS Roadmap, the potential CCS contribution to $CO_2$ emission reductions equals 19% of the total mitigation effort needed by 2050.

### *What does CCS consist of?*

$CO_2$ capture and storage involves capturing carbon dioxide ($CO_2$) produced by using fossil fuels in power generation and industrial activities and then storing it away for a long time (thousands of years) in underground geological formations.

The major application of CCS technology is to reduce $CO_2$ emissions from power generated using fossil fuels, principally coal and gas. However, CCS can also be applied to industries that generate a lot of $CO_2$ in manufacturing and chemical processes such as cement, iron and steel production, petrochemicals, oil and gas processing and others. CCS can also be combined with renewable energy schemes, for instance with biomass, leading to negative emissions (Bio-CCS) or with geothermal energy, combining heat production and $CO_2$ storage.

### *How does $CO_2$ storage work?*

After $CO_2$ is captured at industrial facilities it is then compressed from gaseous form into a dense liquid form, transported by pipeline or ship to a storage location and finally injected deep underground into "reservoir rocks", where pore space exists between the rock grains. Rocks that can be used as reservoirs for $CO_2$ storage are typically depleted oil and gas fields or deep saline aquifers. Overlying impermeable layers of "cap rock" act as a seal to this porous $CO_2$-containing layer, effectively trapping the $CO_2$.

A comprehensive description of $CO_2$

*Fig. 2 - Many potential storage sites lie in the deep geological formations under the North Sea, like the Outer Moray Firth off the east coast of Scotland.*

Geological Storage can be found in the brochure "What does $CO_2$ Geological Storage really mean?" available online in 25 languages for free download at the $CO_2$GeoNet website http://www.co2geonet.com/.

## What is the European policy for $CO_2$ storage?

The implementation of CCS is part of the 2020 European Strategic Energy Technology Plan - SET Plan released in 2010:

"The Commission will reinforce the implementation of the SET Plan, in particular the Joint Programmes of the European Energy Research Alliance (EERA) and the six European Industrial Initiatives (wind; solar; bio energy; smart grids; nuclear fission; and CCS)." (Energy 2020 - A strategy for competitive, sustainable and secure energy).

In the 2050 roadmap the role of CCS and the need to have it widely applied is further reinforced:

"In addition to the application of more advanced industrial processes and equipment, carbon capture and storage would also need to be deployed on a broad scale after 2035, notably to capture industrial process emissions (e.g. in the cement and steel sector)." (A Roadmap for moving to a competitive low carbon economy in 2050).

## How is $CO_2$ storage regulated?

The European Parliament published a regulatory framework in 2009 for the development of appropriate legislation in the European member states, the 2009/31/EC Directive on the geological storage of carbon dioxide. The status of transposition of the European Directive in member states is described in the report "State of play on $CO_2$ geological storage in 28 European countries" produced within the FP7 project "CGS Europe".

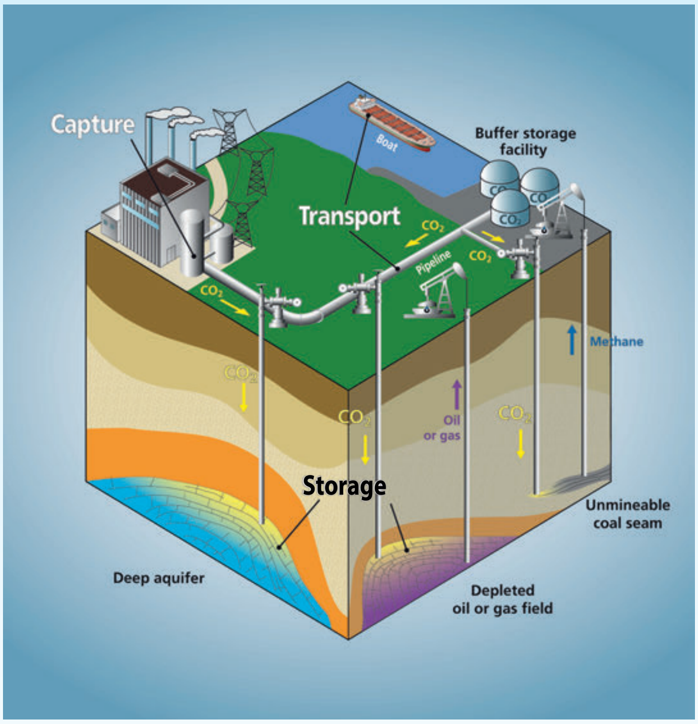

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*Fig. 3 - At power plants the $CO_2$ is captured, compressed and transported via pipeline or ship to its geological storage site.*

## 1.2. UNIQUENESS OF EACH GEOLOGICAL SITE

Conditions underground are highly variable: different kinds of rocks and rock layers, fractures, and fluids (like water and gas), make each site unique. For this reason, to understand whether a geological site is suitable for $CO_2$ storage, SiteChar researchers have refined an approach which quantifies and describes this significant geological variability. The data collection and analysis procedure developed in the SiteChar project for site characterisation has been refined through the study of 5 potential European storage sites that present different underground characteristics.

A summary description of the studied sites is given in Figure 2. Three of them are offshore, in this case the $CO_2$ would be injected under the seabed, while two of them are onshore. From a geological point of view there is no difference between an onshore and an offshore site, although storage implementation is of course easier onshore. The studied sites differ also with regard to the structures that could host the $CO_2$, in some cases depleted hydrocarbon fields in others saline aquifers. Saline aquifers are rock formations that have their pore spaces filled with very salty water, exist in most regions of the world and appear to have a very large capacity for $CO_2$ storage. In the figure we can also see that the type of the hosting rock varies from sandstone to carbonate. Also the layers of rock that would trap the $CO_2$ are of different kinds in the studied sites: shale, salt, marls, marine claystone and mudstone. The choice of these sites allowed the project to study a range of different geological features.

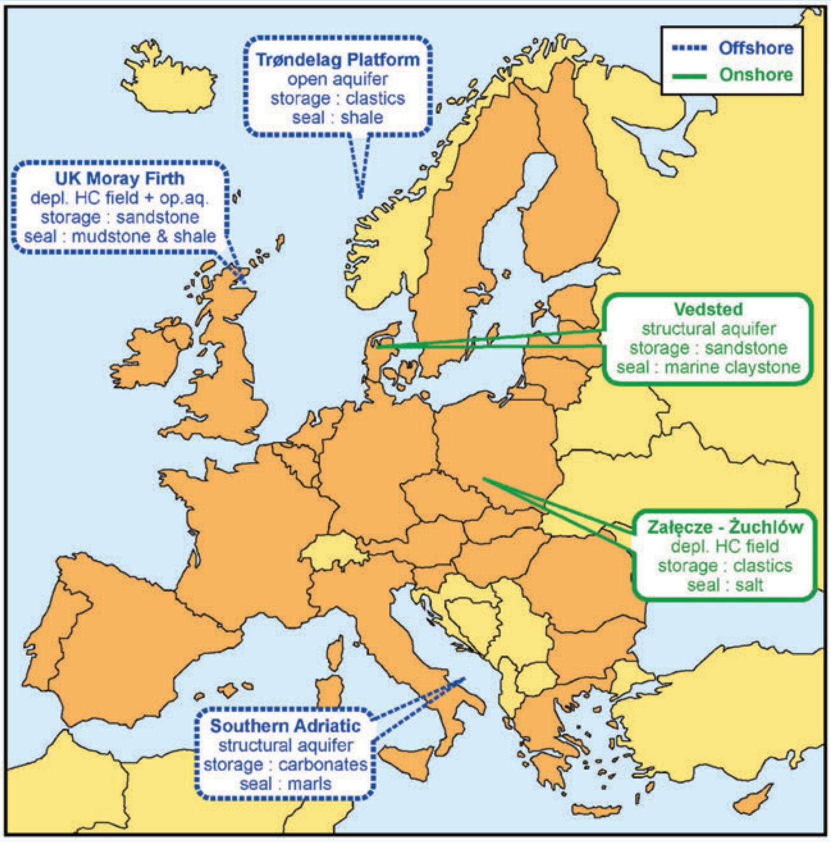
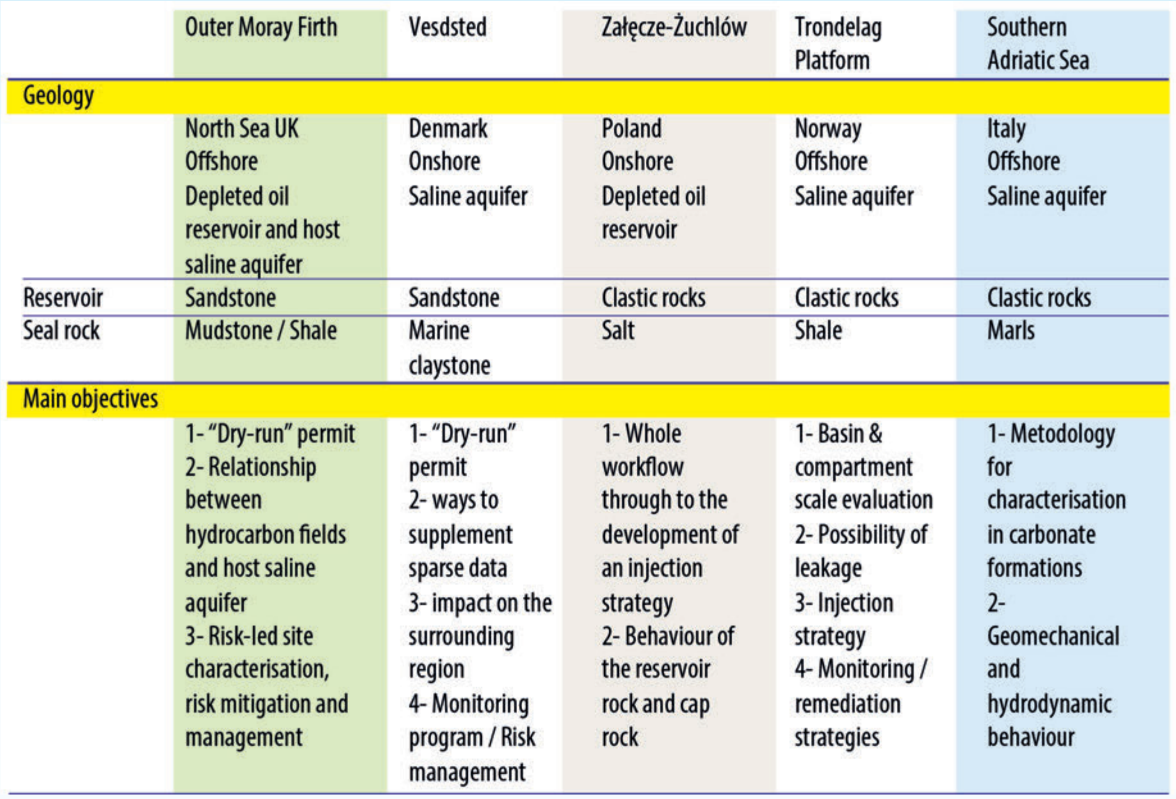


*Fig. 4 - The Sitechar sites portfolio.*

## 1.3. The contribution of the SiteChar project

The SiteChar project has considered different aspects of storage site characterisation: geological, regulatory, social and economic. First of all the characteristics of the underground location need to be considered, checking whether the site has the geological structures that can effectively contain the $CO_2$. At the same time, however, other requirements of a more social and economic nature have to be satisfied. For instance, depending on the kind of geology, the costs for implementation or monitoring could vary, in some cases becoming unsustainable. The social context is also very important for choosing a site: how could the potential site be integrated into the area and other ongoing activities, how does the local population regard the operations and their potential benefits? Finally, all the aspects of a site characterisation process come together when an application is made for the permit to store $CO_2$. The interaction between the technicians and the authorities will have to take into account all those factors that will contribute to the final decision regarding the release, or not, of a permit. The SiteChar project has, for the first time, investigated all of these factors together, in relation to 5 test sites. Here we will summarise, through the example of each site, the different aspects that have been studied.

Because careful CCS site selection is a time-consuming process and because the concentrations of greenhouse gases continue to increase in the atmosphere, it is important that we start to move forward to test and apply this technique in the near future. This is where the SiteChar project hopes to contribute, by helping to develop a roadmap for site characterisation that will ensure that the safest sites are chosen in the most efficient, reliable, and transparent manner.



| | Outer Moray Firth | Vesdsted | Załęcze-Żuchlów | Trondelag Platform | Southern Adriatic Sea |
|---|---|---|---|---|---|
| **Geology** | | | | | |
| | North Sea UK<br>Offshore<br>Depleted oil reservoir and host saline aquifer | Denmark<br>Onshore<br>Saline aquifer | Poland<br>Onshore<br>Depleted oil reservoir | Norway<br>Offshore<br>Saline aquifer | Italy<br>Offshore<br>Saline aquifer |
| Reservoir | Sandstone | Sandstone | Clastic rocks | Clastic rocks | Clastic rocks |
| Seal rock | Mudstone / Shale | Marine claystone | Salt | Shale | Marls |
| **Main objectives** | | | | | |
| | 1- “Dry-run” permit<br>2- Relationship between hydrocarbon fields and host saline aquifer<br>3- Risk-led site characterisation, risk mitigation and management | 1- “Dry-run” permit<br>2- ways to supplement sparse data<br>3- impact on the surrounding region<br>4- Monitoring program / Risk management | 1- Whole workflow through to the development of an injection strategy<br>2- Behaviour of the reservoir rock and cap rock | 1- Basin & compartment scale evaluation<br>2- Possibility of leakage<br>3- Injection strategy<br>4- Monitoring / remediation strategies | 1- Metodology for characterisation in carbonate formations<br>2- Geomechanical and hydrodynamic behaviour |

*Fig. 5 - The SiteChar sites portfolio and the research objectives for each site.*

## *The Norwegian site: the Trondelag Platform*

The Trondelag Platform is a multi-compartment storage complex, which means that the $CO_2$ could be stored in more than one rock formation. The area has been studied by modelling experiments, testing what could happen if the $CO_2$ were to be injected into the rocks. Various aspects were studied, including where the $CO_2$ may move (migration routes) and how the pressure caused by the $CO_2$ injection may be distributed wtihin the injection reservoir. Different simulation tools were used to understand the possible effects of $CO_2$ injection, both in the injection area and more extensively in the region. In this way researchers have been able to understand whether it would be safe to store in this area.

The site has also been evaluated in economic terms. Cost elements for all phases of a storage project off-shore Norway were collected from the literature and the Norwegian petroleum industry. Examples of cost elements are: the cost of an exploration well, the cost of seismic surveys for a given area, the cost of pre-injection modelling, the cost of a sub-sea installation, the daily operational costs (including monitoring activities), and the cost of final site closure.

## *The Danish site: Vested*

The Vested site is an onshore saline aquifer located at 1800-1900 m depth in northern Denmark. Here the research objective was to address all the aspects that need to be considered when a company applies for a storage licence.

A project concept was developed, describing the site and the storage complex, including a possible injection plan and the modelling of the storage performance to estimate the eventual distribution of the $CO_2$ plume. Measures were considered to prevent significant irregularities relative to the potential risks identified, in particular with regard to the development of the monitoring plan.

An important monitoring aspect that was studied relates to the natural values of $CO_2$ commonly found in the soil, which are called by the researchers “baseline” data. Everywhere, in the soil’s pore spaces, some $CO_2$ is present, either due to biological activity in the soil or coming up from deep natural sources.

Baseline data is needed at CCS locations to help differentiate gas anomalies due to

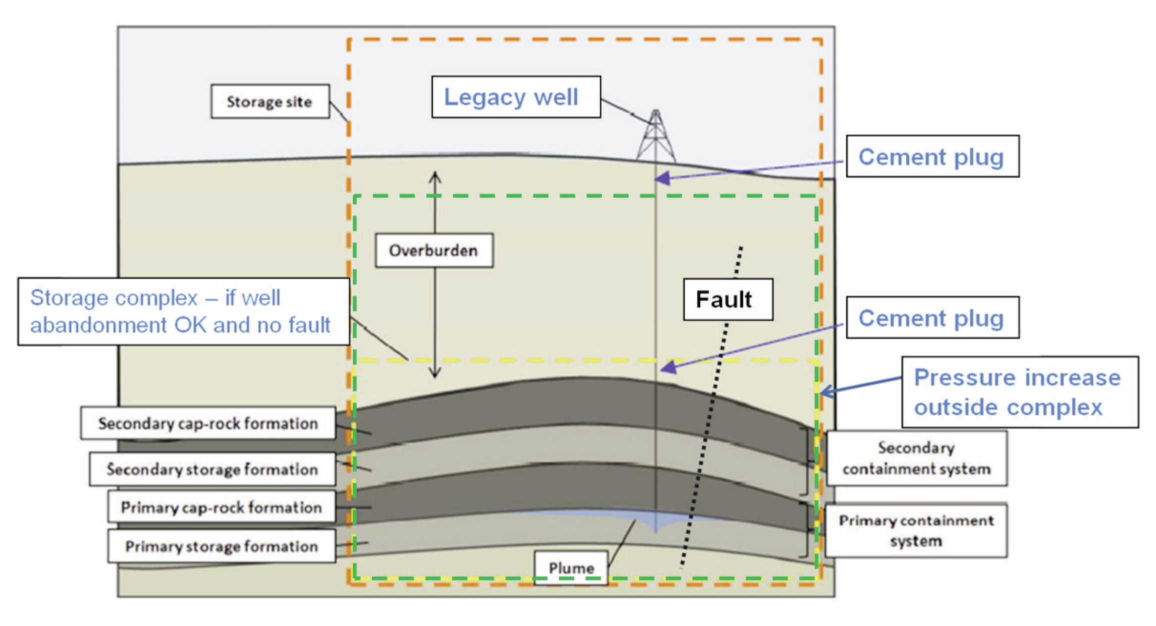


*Fig. 6 - Primary sketch of the storage complex for the Vested site.*

biological processes (such as $CO_2$ produced via respiration in the soil) versus those that may result from a $CO_2$ leak from the storage site. To be able to do this, it is essential to collect information about the $CO_2$ content in the soil *before* any storage operation takes place. SiteChar researchers measured soil gas concentrations and $CO_2$ flux to define the range of natural baseline values and to better understand the influence of such factors as land-use, climate, and seasonality on their variability. The data was collected at the Hobe Agricultural research site (Voulund, central Denmark), which was considered representative of the near-surface environment above a potential northern European $CO_2$ geological storage site.

Another aspect of site characterisation relates to how the pressure builds up underground when $CO_2$ is injected. It is important in relation to other deep subsurface operations and to containment and stability of the site. The operator of a storage site must be able to demonstrate to the authorities how the overpressure propagates in space and time and clarify if mitigation procedures should be established. The possible propagation at the Vested site and any potential effects in the overlying layers has been modelled. The procedures for the modelling have been refined. A specific part of the study has investigated the concept of reducing the pressure in the reservoir by extracting saline water from the aquifer.

Old oil and gas wells also need to be evaluated during site characterisation, to check that they don't become possible leakage pathways for the injected $CO_2$. An old well in the Vested site area was studied and its conditions verified and compared to the requirements outlined in the new $CO_2$ storage regulations, such as the EU Directive on the geological storage of $CO_2$. An important indication emerging from this part of the work concerns the monitoring programme, with the importance of evaluating the relation between different geological elements to assure the best risk management.

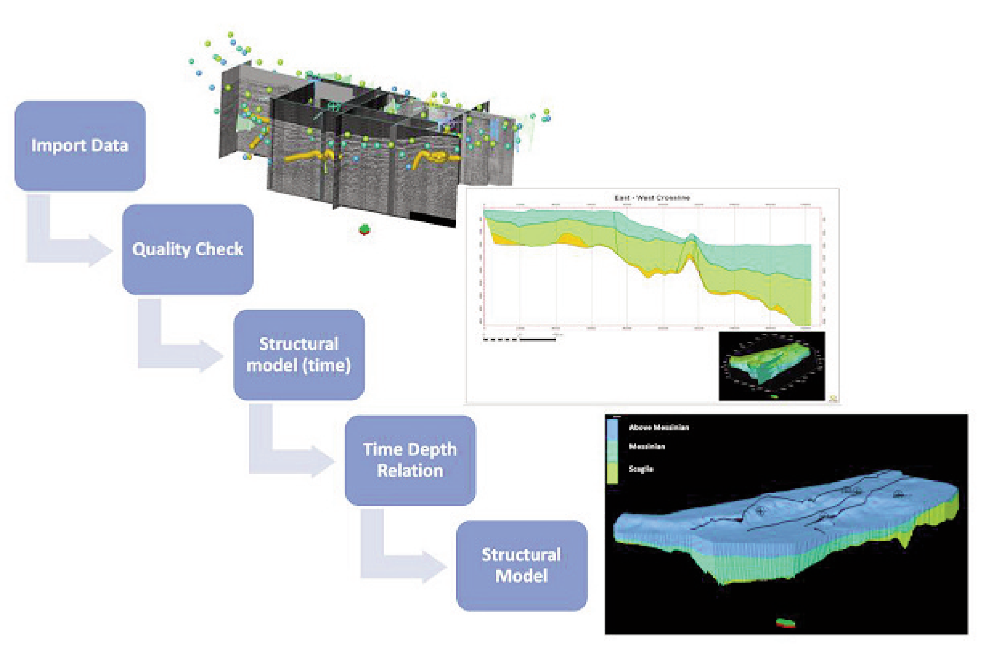


*Fig. 7 - From data collection to the building of a model of the geological structures.*

## The Italian site: Southern Adriatic

The Southern Adriatic site is located offshore Brindisi. It is a saline aquifer close to the main Italian $CO_2$ emission source, the Federico II power plant in Brindisi, where the energy company Enel has launched a pilot plant for $CO_2$ capture in March 2011. Of particular interest are the characteristics of its rocks, which are carbonate formations. This kind of rock can be corroded when $CO_2$ combines with water, so this was an opportunity to increase our understanding of the possible behaviour of these geological formations should $CO_2$ be injected. Another interesting feature of this site is the presence of many faults and fractures.

A model was built to simulate the behaviour of the site in case of $CO_2$ injection, with particular attention to the possible effects of faults and fractures on $CO_2$ migration and to the stability of faults during injection. A variety of situations were tested with different faults' conditions and other geological parameters. Three areas which could be potentially suitable for $CO_2$ storage have been identified and the simulations conducted indicated that the reservoir is able to receive 1 million tonnes $CO_2$ per year for a period of 10 years.

## The Polish site: Załęcze & Żuchlów

The Załęcze & Żuchlów site lies 60 km north of Wrocław and 100 km south of Poznań. It is a depleted natural gas field. The objective of research work in the Załęcze & Żuchlów area was to characterise an onshore gas reservoir in Poland, from the first stages through to the development of an injection strategy. A comprehensive analysis of possibilities for $CO_2$ injection into the natural gas fields was carried out. Detailed analysis of available geological data, and assessment of reservoir and operational performance with a series of laboratory tests and computer simulations helped create the best possible scenario for $CO_2$ injection into deep geological structures.

Integrity analysis of existing wells was undertaken and the application of technical, operational and organizational solutions was examined to reduce risk of uncontrolled release of formation fluids throughout the life cycle of a well.

This took into account two types of issues: 1. improper completion and abandonment of the wells (depleted oil and gas reservoirs); and 2. long-term stability of wellbore materials in a $CO_2$-rich environment (cement, steel). Soil sampling and geochemical analysis are the simplest solution to detecting $CO_2$ leaks at surface. Tracers with different isotopic composition can be added to $CO_2$ injection stream of each well to allow identification of any possible unplanned $CO_2$ migration outside the storage unit.

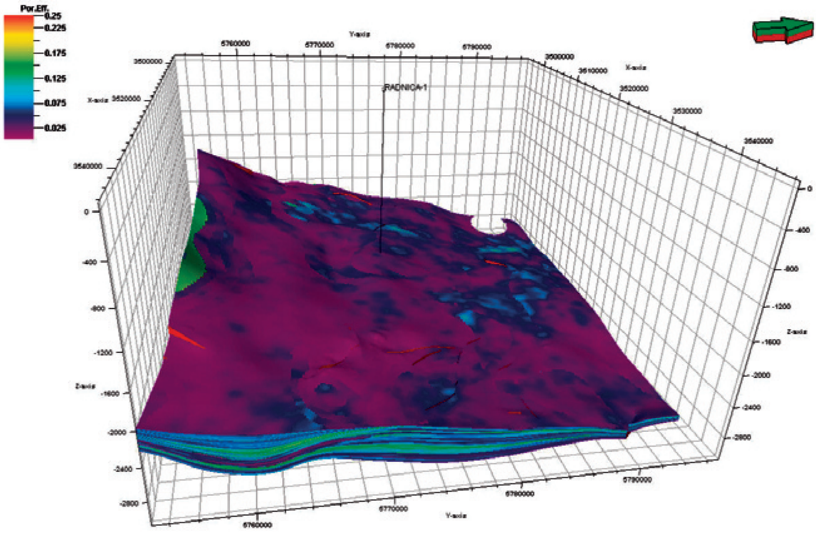


*Fig. 8 - An example of the output of computer simulation, The Załęcze & Żuchlów static model porosity distribution.*

The study of the Polish, as well as the UK site, included research activities with the involvement of the local community, to explore opinions and understanding about CCS technology and to disseminate relevant information. A social site characterisation process was undertaken to support cooperation among stakeholders and the public. This produced a 'social map' of local opinion shapers. Then, an innovative formula for enhancing cooperation was tested, called "Focus conference", which aimed at building trust and facilitating the development of informed opinions. The participants had ample opportunity for getting information from key stakeholders and for exchanging it, finally expressing their own point of view on the conditions for CCS acceptability in the area.

*Fig. 9 - Listening and learning about $CO_2$ storage at the Polish Focus Conference.*

## *The United Kingdom site: the Outer Moray Firth site in the North Sea*

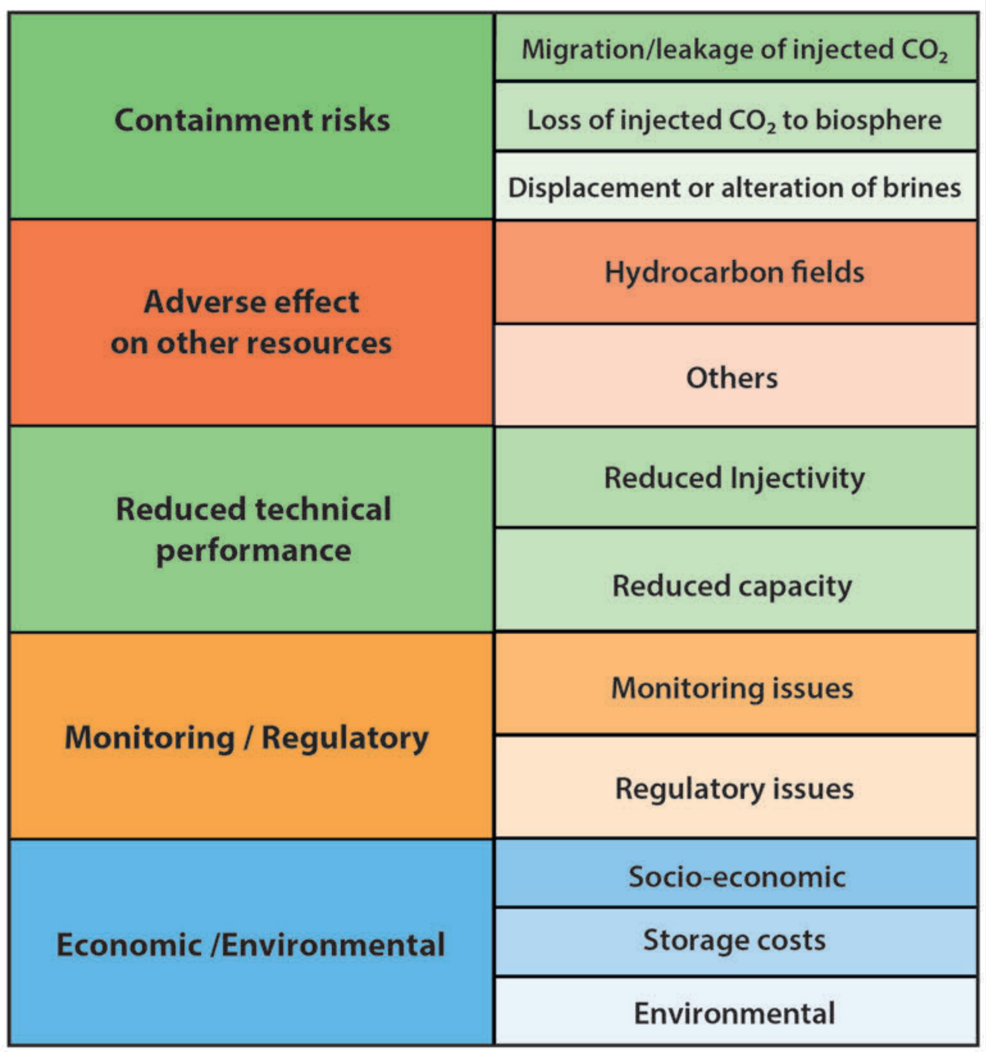
The UK site lies offshore in the northern North Sea off the east coast of Scotland in the Outer Moray Firth, known from North Sea oil and gas exploration and production. The SiteChar research project assessed a multi-store site, in which the $CO_2$ could first be injected and stored in a depleted hydrocarbon field, later the $CO_2$ could extend into the surrounding saline aquifer sandstone.

Containment within the site will be beneath cap rocks that have demonstrated trapping of hydrocarbons for millions of years.

At this site the researchers and the Scottish authorities were engaged in testing the complete procedure that should be followed to get a permit for storage. After assessing the risk of $CO_2$ escape from the reservoir and other possible risks, they undertook a number of studies to understand how these risks could be minimised.They simulated what would happen if $CO_2$ was injected. Specific cases were considered, such as: what could be the effect of $CO_2$ injection on geological features, like existing faults and the containing cap rock? Where would the $CO_2$ flow if the site was excessively overfilled? Would the water from the saline aquifer have to be extracted to manage the pressure underground? Would abandoned wells become potential leakage points? What chemical changes could take place in the reservoir rocks?

They also studied the feasibility of an effective monitoring of the storage site, developing monitoring and preventative measures plans and provisional corrective measures and post-closure plans.

The results of the whole process for developing a permit application, both for the UK and the Danish sites, were reviewed by independent experts and compared against the requirements in the European $CO_2$ Storage Directive and the associated Guidance Documents. For the UK site, the guidance documents produced by the UK Government were also used. More information about the outcomes of this process can be found in SiteChar technical brochure (Anna Korre and the SiteChar partners, 2013). For more detail two public deliverables are available on the SiteChar website: D2.1 Synthesis and lessons learned from the application of the SiteChar workflow; D2.4 Best practices and Guidelines developed from the SiteChar project.



| | |
|---|---|
| **Containment risks** | **Migration/leakage of injected $CO_2$** |
| | **Loss of injected $CO_2$ to biosphere** |
| | **Displacement or alteration of brines** |
| **Adverse effect on other resources** | **Hydrocarbon fields** |
| | **Others** |
| **Reduced technical performance** | **Reduced Injectivity** |
| | **Reduced capacity** |
| **Monitoring / Regulatory** | **Monitoring issues** |
| | **Regulatory issues** |
| **Economic /Environmental** | **Socio-economic** |
| | **Storage costs** |
| | **Environmental** |

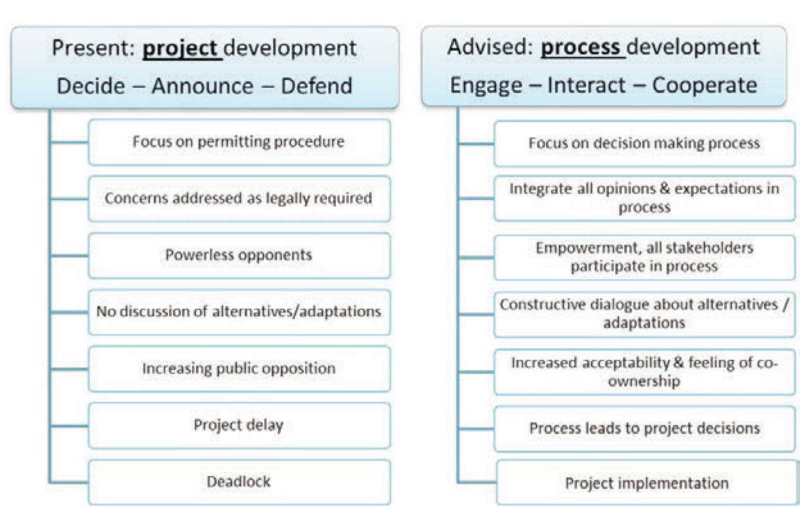
*Fig. 10 - Over-arching risks to be addressed by site characterisation. Each perceived risk has been described and categorised and site characterisation work was targeted to understand and reduce the risks. Categories of risk seen in the figure (right) were grouped in five over-arching risks (left). The SiteChar characterisation approach is "risk led" to prepare the required components of a storage permit application.*

# RAISING PUBLIC AWARENESS AT PROSPECTIVE $CO_2$ STORAGE SITES

The aim of the SiteChar project was to develop an effective methodology for the preparation of $CO_2$ storage license applications, incorporating all the technical and economic data, as well as the social dimension. To advance public awareness social site characterisation and public participation activities were conducted at two prospective CCS sites: an onshore site and an offshore site. The onshore site is the Zalecze & Zuchlów 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.

Results provide insight in 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. A summary of the results can be found in the Final summary report on public awareness, D8.5.

### *Shifting focus from project to process in decision making.*



A constructive stakeholder and citizen's participation process increases the likelihood of public acceptability of a $CO_2$ storage project. This implies a shift in focus from project to process in decision making. Such a shift is illustrated in the figure above, taking inspiration from the NEA report "Stepwise Approach to Decision Making for Long-term Radioactive Waste Management, Experience, Issues and Guiding Principles" (2004), in which it is stated that "The new dynamic of dialogue and decision-making process has been characterized as a shift from a more traditional "decide, announce and defend" model, focused on technical assurance, to one of "engage, interact and co-operate", for which both technical assurance and quality of the process are of comparable importance to a constructive outcome".

*From the position paper of the Scottish Focus Conference participants: "We believe it important that an exit strategy should be developed (…) to address how to scale down and then ultimately exit the CCS industry completely at a later point in the future".*

*From the position paper of the Polish Focus Conference participants: "The majority of the group thinks that there are too many uncertainties to clearly opt for carbon capture and storage technology (CCS)".*

# PART 2. CHOOSING A GEOLOGICAL SITE FOR STORING $CO_2$ UNDERGROUND

The selection of a storage site is a complex process that needs to take into account a variety of aspects, all interrelated, involving a multiplicity of expertise. This is done by a multi-disciplinary team, to make sure that the safety and security of storage is ensured and considered from all angles. Regular contact between operator and regulator teams is recommended. The role of the regulator in steering the choices of the operator with regard to site choice, characterisation and monitoring is fundamental. The whole process is aimed at minimising the risk and maximising the safety and security of storage.

## 2.1. WHAT DO WE NEED TO KNOW FOR GOOD SITE CHARACTERISATION?

To ensure that we make a good site selection three areas have to be investigated: the geology, the economy and the social context. The information thus gathered converges in the licencing process - where the regulator plays a fundamental role in ensuring that all the required steps are respected and that the quality of the adopted parameters is sufficiently high.

***Understanding the geology***: each specific underground location is unique and invisible to our eyes, however geologists have developed methods and criteria to better understand deep geological strata, how they developed in the past and how they are evolving presently. When choosing a site this knowledge will be the starting point on which the collection of more specific information will be built. This will enable the technicians to understand the geological features of the potential reservoir, for instance the porosity of the rocks or the tightness of the caprock, the characteristics of geological strata and the presence of faults and fractures.

When the geologists have collected the necessary data about the subterranean location, they use this information to develop models which help them interpret the unique features of each site. Different kinds of models are necessary to describe and simulate all the complex mechanisms that might take place in the underground should $CO_2$ be injected.

First of all we need a model of the geological features in the underground, this is called a static model, because it describes the characteristics of the rocks but does not tell us anything about how the situation can change in time. This is the object of a different kind of model, called dynamic or geomechanical model, which tries to describe how the situation in the underground might evolve when different conditions change. For instance when the injected $CO_2$ alters the pressure of the fluids or when some seismic movement takes place. Yet another kind of modelling simulates the chemical interactions between the $CO_2$ and the host rock, for instance how the $CO_2$ interacts with the existing water in the reservoir or whether it corrodes the rocks.

Knowledge about the geological conditions of the potential $CO_2$ storage site includes a detailed investigation of the wells that might be already be present in the area, especially in the case of depleted oil and gas fields.

When all these simulations and investigations have been undertaken, by bringing together the information gathered, the scientists will be able to develop some models about the possible gas migration pathways in the underground and therefore evaluate the suitability of the site for $CO_2$ storage. Due to the variability of subsurface characteristics and conditions, the geological traps that can retain $CO_2$ can be represented as complex systems with strong and weak points which need to be well known and understood to make sure the storage takes place in a safe manner.

***Evaluating economic convenience***: at every step of a site characterisation process economic aspects have to be taken into account. Economic assessments in the SiteChar project have indicated that costs are not easily calculated and that they will be very specific for each site.

***Interacting with the local communities***: the knowledge required for selecting a $CO_2$ storage site includes understanding of the social context and of local communities' perception of the technology and its implementation. Collecting information on the social and geographical characteristics of the site is a process called social site characterisation, which includes data collection about the local community's perception and attitudes about CCS and direct interaction and information activities with local stakeholders and the public. In SiteChar this was done for two sites, the UK site offshore Scotland and the onshore Polish site.

*Fig. 11 - Exchange session during the Polish Focus Conference.*

## 2.2. STEP BY STEP TOWARDS SITE CHOICE: THE WORKFLOW

What is a workflow? A workflow is a description of the steps required to complete a process, here it refers to the site characterisation process.

The SiteChar workflow describes the subsequent phases that lead to selecting a site for $CO_2$ storage.

The workflow structure has been drafted based on expert input and subsequently developed and detailed through the work performed on the five sites selected for the study.

Making the choice regarding the storage of $CO_2$ at a given site is the final step of a complex back-and-forth process which involves the operator, regulators and local communities through a gradual evaluation of geological opportunity, economic convenience and social acceptability of the storage project.

The site characterisation and site permitting procedure developed in the SiteChar project is “risk-based”. In other words, the goal of this work will be to define all potential risks, estimate their probability and possible impacts, and determine if those risks can be minimised in the eventual development of the site. If the risks are too high, or they cannot be minimised at a reasonable cost, then that site has to be abandoned as a potential storage location. Risks must be assessed throughout, from a more qualitative assessment conducted during the initial screening phase, through the data collection and interpretation phase, all the way until the final quantitative risk assessment.

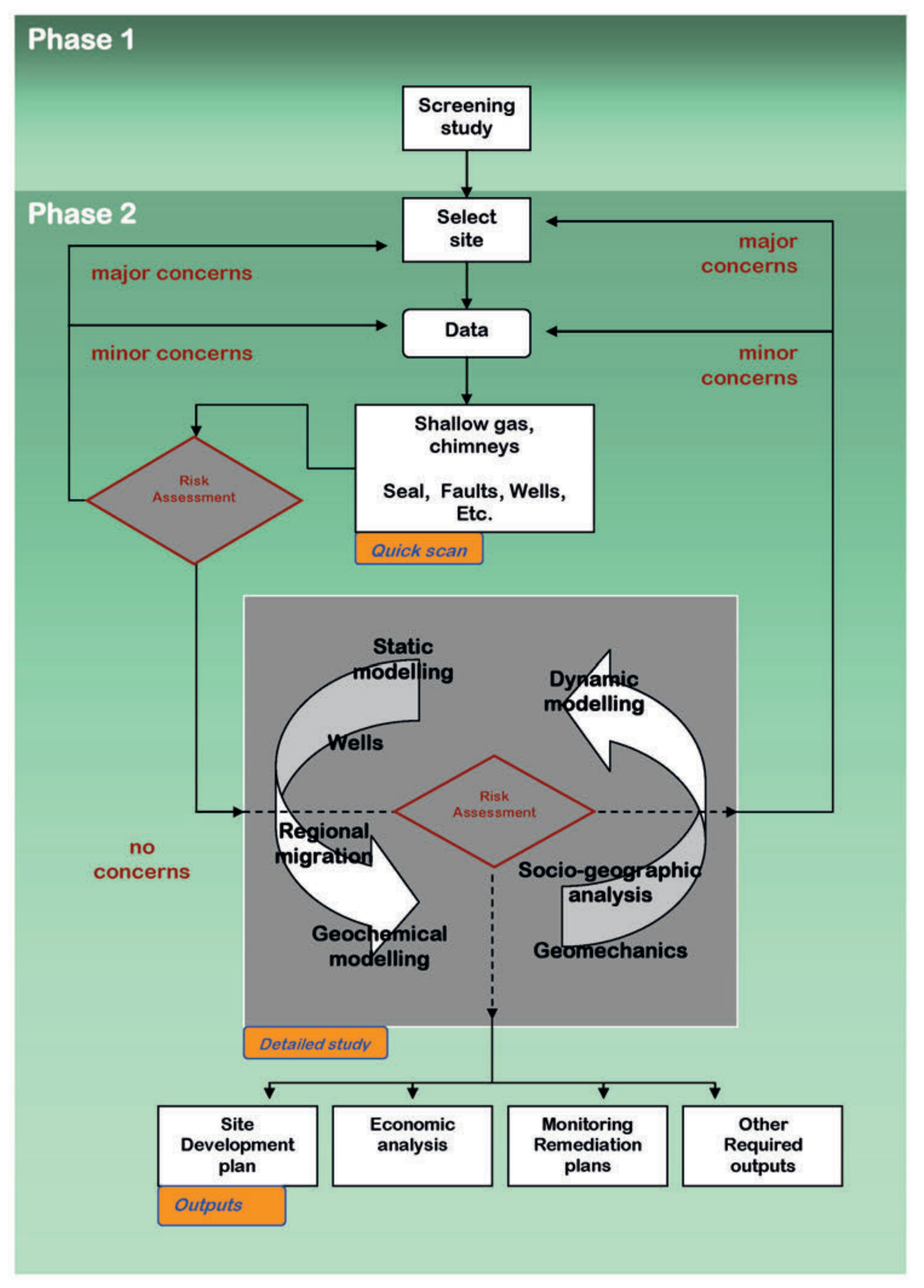
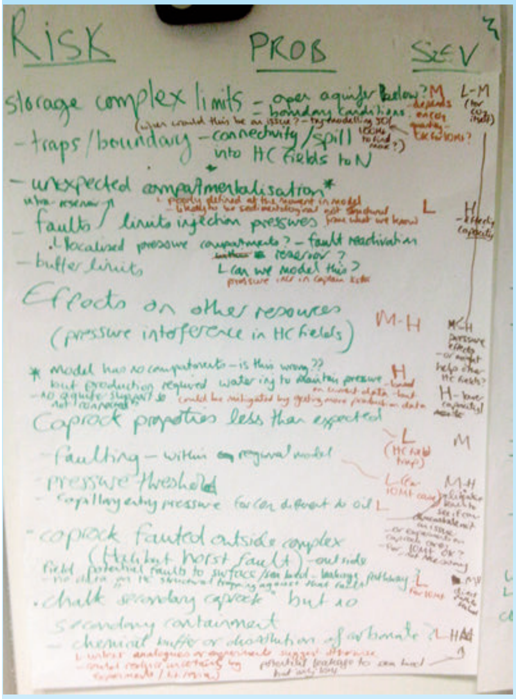


*Fig. 12 - SiteChar workflow: a methodology for site characterisation, validated through insight from research on the SiteChar sites portfolio, to guide the implementation of the EC $CO_2$ Storage Directive and OSPAR regulation in Member States.*



RISK PROB SEV

storage complex limits – open aquifer below? M L-M

– boundary conditions

– traps/boundary – connectivity/spill into HC fields to N

– unexpected compartmentalisation*

faults / limits injection pressures L H

– buffer limits

Effects on other resources (pressure interference in HC fields) M-H M-H

* Model has no compartments – is this wrong?? H

Caprock properties less than expected L M

– faulting – within regional model

– pressure threshold

– capillary entry pressure for $CO_2$ different to oil L

– caprock faulted outside complex (Halibut horst fault) – outside field

. chalk secondary caprock but no secondary containment

– chemical buffer or dissolution of carbonate? L-H

*Fig. 14 - Hand written notes from a risk assessment workshop by experts in SiteChar. Perceived risks are identified, based on existing knowledge and expertise, and each is assigned a probability of occurrence and likely severity of consequence if the risk does occur. Site characterisation works to reduce these risk to as low as reasonably possible.*

As shown in the Figure 12, an initial screening process defines a short list of promising sites, which are then studied using an iterative approach which re-examines all the data in the light of the new data which is progressively acquired. The first screening is made on the basis of existing data, since the acquisition of geological data is a time consuming and costly process.

The more detailed study part of the process consists of the application of different tools that aim to answer specific questions regarding the behaviour of the $CO_2$ underground and whether it will be safely trapped. Throughout this procedure risk assessment is performed, progressively becoming more complex as more and more data is produced. What follows is a short description of the various steps and tools used, and the questions that they are trying to answer.

## Workflow Phase 1. Screening of potential areas for storage

When we want to reduce the emissions of an industry or of a power plant we need to capture the $CO_2$ and find a safe and appropriate site for storing it. Because of the costs, logistics, and permissions related to installing a pipeline, the closer the storage site is to the source of the gas the better. This means that the search will probably begin within a certain radius around that source, perhaps up to a couple of hundred kilometres.

The storage site will have to have enough space, which in technical terms is called “capacity”, for the amount of $CO_2$ produced, and must be capable of receiving the $CO_2$ at the speed that it is delivered. The “injection rate”, i.e. how much $CO_2$ we can inject in a given time frame, depends on how quickly the gas flows into the reservoir, its “permeability”, and how much you have to push to get it to enter, its acceptable “injection pressure”.

The initial screening for the best site will therefore be based on things related to the $CO_2$ source (location, total volume, rate of production) as well as things that make a storage site physically possible (proper depth, good permeability, etc.) and safe (good caprock, no leaking wells, etc.). This search involves a review of existing information for the area, including geological maps, descriptions of the geology found during the drilling of existing wells, information from geophysical surveys like seismics (see box " A seismic survey, what does it mean?"), knowledge about the possible occurrence of earthquakes or active faults, and possible conflicts with other resources that are used in the area like oil fields or groundwater extraction. The process of assessing potential risk begins immediately during this initial screening process, creating an early, qualitative description of large scale issues and environmental or social restrictions. Specialists in various fields of expertise related to CCS (such as reservoir engineers, geologists, geochemists, computer modellers, etc.) will examine the existing data and assess if there are any large, obvious reasons why an area should not be considered (in other words, any obvious risks).

The final outcome of this initial screening stage is the creation of a short list of promising sites that appear to meet the needs of safety and capacity, but which need further study to prove that they are appropriate. It is likely that the most promising of these will be chosen for the more detailed study conducted during the subsequent "site characterisation" stage.

### Workflow Phase 2. Collection of all avalaible data on the eligible site and experts' evaluation of possible risks

The first step in the site characterisation process is the collection of all available data on the specific site. Work during SiteChar has shown that gaining access to some of this information, which may be owned by other companies, archived by the government, or produced by research institutes, can be very time consuming and thus this process must be started immediately. As this is data collected for other purposes, and gaps likely exist in the types of data collected, it may be necessary at this stage to collect new data that will fill any critical knowledge gaps. Abandoned oil field sites will likely have lots of data available, whereas saline aquifers are usually less known.

Based on this new, larger, and more storage-related dataset, the experts will conduct a quick scan, once again, to see if there are any obvious risks or other factors that exclude the site from being considered as a storage location. These might include such things as a large number of potentially leaky wells from oil and gas operations, a poor caprock or the existence of major faults. If the prospective storage site passes this step then the data is examined to define knowledge gaps where more information is needed to accurately assess the appropriateness of the site and help focus the subsequent detailed study on the items of most concern for that site. Possible risks are ranked based on the probability and severity of their possible occurrence and these results are summarised in a table (known as a "risk matrix"). This matrix focuses subsequent modelling and research on those items that, based on the initial data, have a high probability and a high potential severity. At this stage public participation is strongly encouraged to ensure a transparent communication about the evaluation of potential risks. The work done in SiteChar has shown that the public, local stakeholders, and non-governmental organizations (NGO's) should be invited to participate and play an active role in the qualitative risk assessment process. It is hoped that by showing that the studies are in-depth, and that the work has been conducted in a transparent and responsible manner, the project can earn the trust and support of the local population.

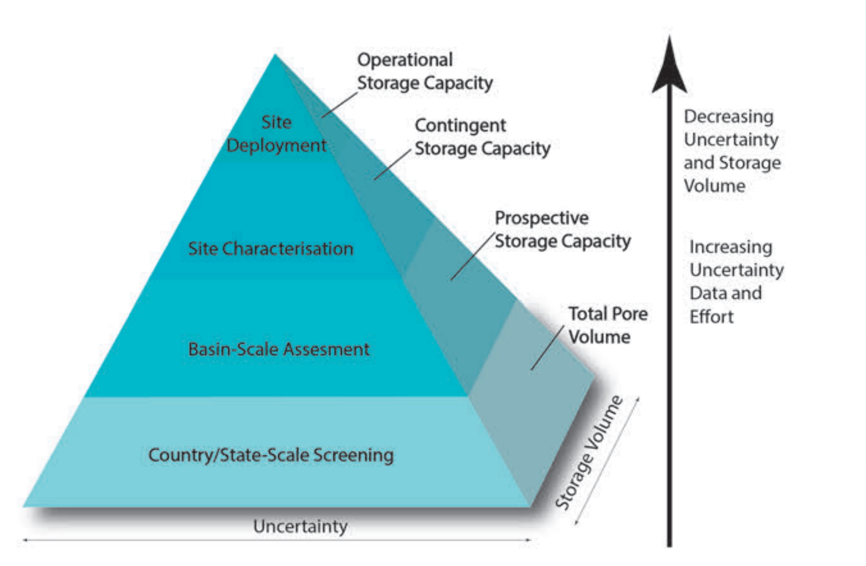


*Fig. 15 - The screening study is the first element of the workflow, based on readily available but limited site data. Criteria used at this stage are for instance: total storage capacity, injection rate, distance, availability, surface use.*

## Workflow Phase 3. The detailed characterisation of the site

The sites which are still considered eligible after all the previous evaluations have been undertaken are now investigated in more detail. Based on that assessment, experts will have identified the possible weak points in the system, which are now to be checked and trialled. New data is collected to fill knowledge gaps and address uncertainties. Based on an integration of old and new data and understanding developed up to this point, models are built to get a full picture of the geology and of what could happen should the $CO_2$ be injected. Consistency verification and integration of the outputs of all the models is then performed. This is the most complex and time-consuming part of the site characterisation process.

### The study of present underground conditions and baseline values

The basis for the site characterisation process and decision making is a good understanding of the present conditions of the potential storage site area. This includes the geological characteristics of the underground and of the surface or near surface environments and their socio-economic implications.

#### BUILDING GEOLOGICAL MODELS

As a first step the operator will collect the additional information required for developing a model of the geology in the area being considered for storage. This includes understanding what types of rocks are present, how their characteristics change with depth and over the study area, if there are there any wells and if they go into the reservoir, what kind of fluids (like gas and water) are present in the rocks, the existence of any faults, etc. The collection of the necessary data and its organisation using dedicated computer software results in the creation of a three dimensional representation of the underground which is known as a "static model". Although data for the static model will come from many sources, two of the most important are seismic surveys and borehole cores (see box "What is a borehole and what we can learn by it"). All information collected from the borehole cores and the well logs, as well as other sources of data, will be input into the geological static model to make it more accurate and realistic. Because there will always be uncertainties as a function of the amount of data that can be collected, its location, how uniformly it's distributed, its quality, etc., it may be considered necessary by the competent authority and/or operator to develop more than one static model and by comparing them increase understanding of uncertainties. Because the collection of data to construct the static model can be time consuming and possibly expensive (especially if new seismic or borehole data must be collected) this phase should be started as early as possible. The static model, once created, forms the foundation for all the other models and for the risk assessment itself.

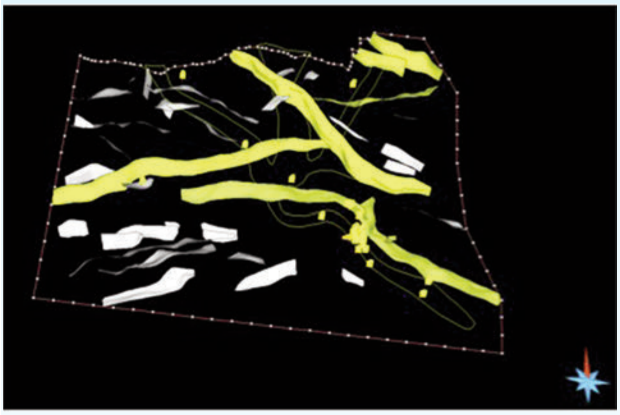


*Fig. 16 - A 3D 'static' computer model of geological faults in the subsurface constructed as part of the characterisation of the UK storage site in SiteChar. The position of the faults in the model (yellow and white) has been constructed from seismic survey and borehole data already obtained by oil companies in their search for oil and gas in the area.*

## A SEISMIC SURVEY, WHAT DOES THIS MEAN?

A simplified analogy of a seismic survey would be the echo you hear when you call out across a valley. Picture yourself walking along a long canyon that becomes narrower and wider along its length. At regular points along your walk you call out and measure the time it takes for your voice to come back after it has bounced off the opposite canyon wall. Knowing that time (which is the time it takes for the sound wave to go to the wall and then come back, the "two-way travel time") and the speed of a sound wave in air, you would be able to calculate the distance to the opposite wall (that is the canyon width) all along your walk. Although much more complicated the basic idea is similar for a seismic survey. Seismic surveys are performed along a line (or multiple parallel lines) on the ground surface by sending a mechanical wave into the ground (by pounding on the ground or using mini-explosions) at points along that line and measuring the echoes as that wave is bounced back from various rock contacts underground. Instead of hearing a single echo, multiple seismic echoes are recorded in time as the wave is reflected back from deeper and deeper rock contacts. Instead of a single velocity in air, the velocity of the mechanical wave changes as it encounters different rock types with different characteristics. Putting all these echoes together along the entire line results in a representation of how the geology changes with depth along that line (known as a "seismic-section"). The types of rocks associated with each echo, and their depth corrected for the changing velocity, is determined using borehole data.

## WHAT IS A BOREHOLE AND WHAT CAN WE LEARN FROM IT

Boreholes are deep holes drilled into the underground using specialized drilling equipment. A simple example would be a well drilled into an aquifer to pump out drinking water. Whereas water wells are usually less than 100 m deep, the boreholes drilled for CCS must be at least 800-1000 m deep so that they enter into the proposed storage reservoir. In addition, while some of these will be normal vertical wells, others will start off vertical and then will change direction and become almost horizontal within the reservoir itself. Rock samples can be collected during the drilling, depending on the type of drill used. The faster and more common drill basically pulverizes the rock, resulting in a stream of mixed water, mud, and rock chips coming to the surface where they can be collected. The other type instead cuts an intact cylinder of the rock (a "core") which is brought to surface for examination. Both techniques can be used on the same hole, with the pulverizing method used to go quickly through the less important parts and the coring method used for the interesting parts. Of course what you consider as "interesting" depends on what you are looking for – an oil company is probably only interested in the oil reservoir rocks, whereas a company wanting to do site characterisation for $CO_2$ storage will be interested in both the reservoir and the caprock. The samples that are brought to surface can be measured to understand how much $CO_2$ the reservoir can hold (in other words the volume of the rock voids, its "porosity"), how quickly it could be pumped in (its permeability), the strength of the rock, the types of minerals present and how quickly or slowly they react with $CO_2$, etc. Finally once the borehole is finished, geophysical tools can be lowered into it to measure changes along its depth (called "well logs").

### COLLECTING BASELINE MEASURES

Any change in the system can only be understood with reference to its initial conditions. While building the geological model, a dataset of baseline measurements starts to be collected, such as initial pressure distribution in the reservoir, the minerals present, the chemistry of the deep groundwater, and the seismic response of the local geology, amongst many others. Other types of data are collected at a later stage, when the site suitability has been proven and are used for the development of the monitoring plan. Two important examples are the chemistry of aquifers used in the area as a source of irrigation or drinking water and the chemistry and flux of gases in the soil. These environments must be measured both to see if there is a leak in the area, and to understand whether if a leak occurs will it have any impact on water resources or human safety. Baseline data is particularly important here since these environments are more dynamic that those in the deep underground, because of exchange with the surface (like rainfall or heat) and biological processes. The concentration and flux of $CO_2$ in the natural environment, pre-injection, is also very important because $CO_2$ is produced naturally by plant roots and microbes in the soil, and thus it is critical to be able to understand the shallow biological $CO_2$ values and distribution so that it is not mistaken for $CO_2$ leaking from the reservoir. In fact work within SiteChar showed how $CO_2$ soil concentrations and fluxes in a natural pristine environment changed significantly as a function of both time of year and the type of use of the land.

*Fig. 17 - An example of field measurement of $CO_2$ flux in the soil.*

## *Understanding how underground conditions would change with the injection of $CO_2$*

To understand how things could develop when we start injecting $CO_2$ underground, we have to move from the static geological model to one that predicts how things will develop as a result of our actions. To do this we need to create dynamic models and conduct migration path analyses.

### DEVELOPING DYNAMIC MODELS

These models are useful to estimate how the modifications would change the system over time. This modelling approach can examine many different types of parameters that would change or evolve with the injection of $CO_2$. One of these models describes how the gas will flow into the reservoir and how far, how quickly, and in what direction, depending on many parameters like the $CO_2$ injection pressure and rock characteristics like porosity and permeability. These include hydrodynamic models to look at the movement of the fluids, geomechanical models to examine rock strength, and geochemical models to estimate potential changes in mineral and water chemistry. These dynamic models use mathematical formulas that mimic the laws of nature and, combined with data from the static model, can be used to predict possible physical and chemical consequences of $CO_2$ injection. They will be used to help predict how much $CO_2$ can be stored, how rapidly we can safely inject it, where the injection wells should be located, if the $CO_2$ will remain trapped both in the short term (during injection) and the long term, what form the $CO_2$ will

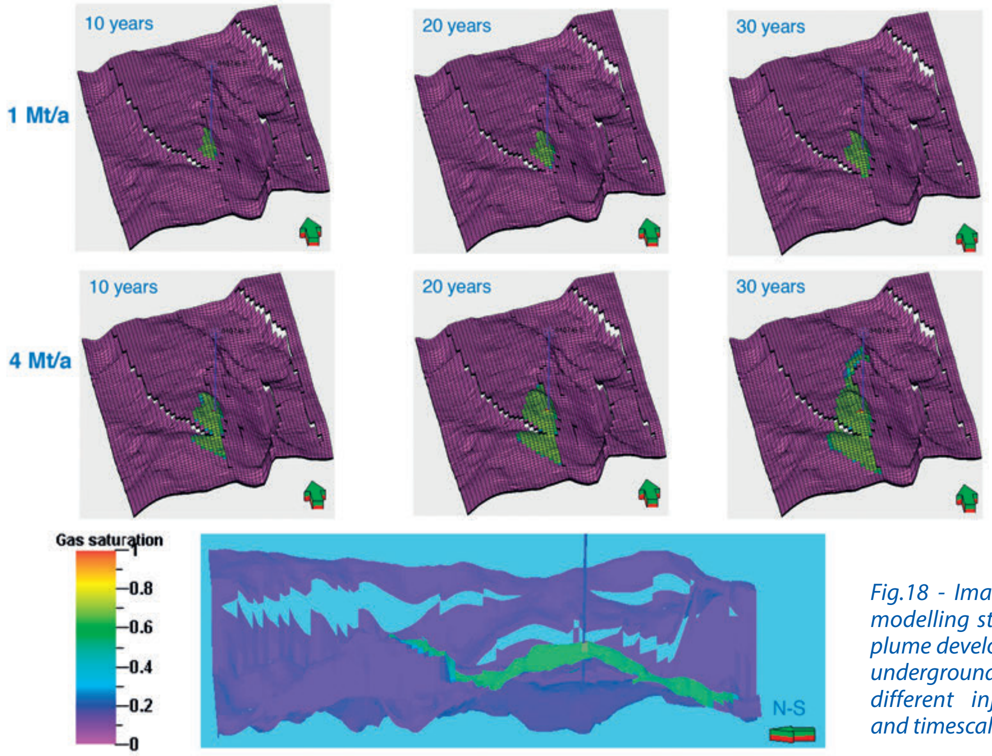


*Fig.18 - Images from the modelling studies on $CO_2$ plume development in the underground (Imperial) at different injection rates and timescales.*

be in (liquid, dissolved, precipitated as a mineral, etc.), if the reactions between the $CO_2$ and the rocks will change the reservoir porosity or permeability, if the $CO_2$ injection will push the existing fluids, like salt water, into a drinking water aquifer, and various other important issues related to site safety and site feasibility.

### EXPANSION OF THE $CO_2$ IN THE UNDERGROUND AND POSSIBLE MIGRATION PATHWAYS

Migration path analysis is an extension of the dynamic modelling, and is performed to estimate where the $CO_2$ goes over the long term, if it arrives at any locations that may allow it to leak from the reservoir (such as large faults, leaky boreholes, or an area with a poor caprock), and to estimate how much $CO_2$ might leak from those pathways.

### EVALUATING THE RESISTANCE OF THE ROCKS TO INJECTION PRESSURE

To push the $CO_2$ into the reservoir rock, a pressure will need to be applied. It will be important to understand how much pressure can be used for optimal injection without affecting the geological system. The amount of pressure will depend on the reservoir and caprocks at each individual site, because if you apply too much pressure there is the risk that a previously sealed fault or fracture may re-open or new fractures may form, thus creating potential pathways where $CO_2$ might leak. Measuring and estimating the strength of rock under natural or modified pressures lies in the field of geomechanics. This work also requires models to be created and run to estimate the impact of the injected $CO_2$, with input data describing the system coming from many different sources. First the local forces must be defined, which are the initial "stress" and "strain" on the rocks caused by the weight of the rocks themselves and the fluids within them. Any faults or fracture zones in the area, and their mechanical characteristics, should also be defined. Then ideally core

## CAPTURING COMPLEX NATURAL VARIABILITY

Because of the variability and complexity of nature the parameters used in the models will not have a single value but rather a range of values. Because of this many simulations will need to be conducted with these models, by putting in different parameter values within that range to give a more realistic representation of how variable the estimates might be. These simulations should "err on the side of caution", in that they should present both the optimistic and the more pessimistic results (based on actual site data collected) so that all risks can be assessed and the site objectively characterised. In other words models should be conservative to ensure safety and storage success.

samples of the reservoir, caprock, and other overlying rocks, collected from the deep boreholes, should be tested using special equipment that measure how much force, and in what direction, a rock can resist before it breaks. This defines the rock strength.

These data, combined with results from the static, dynamic, and geochemical models, will be inserted into the geomechanical models to estimate the maximum amount of pressure that can be applied and what areas of weakness may exist in the system. Because of this it is critical that dynamic and geomechanical modelling be conducted in close collaboration.

### INTERACTIONS BETWEEN THE INJECTED $CO_2$, UNDERGROUND "FLUID" AND ROCKS

When the $CO_2$ is injected in the underground, it partially dissolves in the water which is found in the reservoir, making it slightly acidic. Acidic water can then react with the rocks. The speed, extent and the impact of these reactions on rock characteristics and water chemistry will depend on the types of minerals present in those rocks, how quickly the CO2-containing water flows through the rocks, the temperature and pressure of the rocks, and the initial chemistry of the water. In other words, potential $CO_2$ reactions will be very site dependent.

Studies have to be performed on three different areas, the reservoir rocks, the caprock, and the cements that are used in any wells that occur in the area. For these three categories it is necessary to know the types and amounts of minerals that are present. Samples from borehole cores can usually supply this information for the first two, however the composition of well cements can sometimes be quite different (depending on when the well was drilled and when it was closed) and samples can be difficult to get. If core samples are available for any of these three types, direct experiments can be conducted on them to better understand the types and speed of any reactions with water that has dissolved $CO_2$. These can consist of crushing the rock, mixing it continuously in a container with $CO_2$-water, and measuring the changes in water and minerals (a "batch experiment"). This gives an indication of what might happen, but in the real world the reactions will occur much more slowly because there is less direct contact between the water and the rock. Experiments can also involve forcing $CO_2$-rich water directly through the core rock pores (a "column experiment") in a way that is more similar to that which will occur underground, however it is a very slow process.

Regardless of whether direct experiments can be conducted, data related to the mineralogy, mineral surface area, porosity, and water chemistry of the site can be inserted

## GAS - WATER - ROCK INTERACTIONS: DISSOLUTION AND PRECIPITATION OF MINERALS

The two most important reactions are the dissolution and precipitation of minerals. Dissolution means that some minerals of which the rock is formed dissolve into the water, which enlarges the voids in the rock (porosity) and may increase how well those voids are inter-connected (permeability). This process can be good for the injection process because it creates more space for the $CO_2$ and may make it easier for it to flow into the reservoir. On the other hand it can potentially be a problem if it creates a pathway through which the $CO_2$ could escape. The process of precipitation is exactly the opposite, as it involves the formation of new minerals because the water is no longer able to keep the dissolved elements in solution(in other words, the water is "over-saturated" with respect to that mineral). The new minerals precipitate on top of the old ones and have the overall effect of decreasing both porosity and permeability. The good thing about precipitation is that the minerals that are forming tend to be carbonates, which means that they contain a large amount of $CO_2$ that is permanently trapped in a solid form. This process can also potentially seal possible gas migration pathways. The potential down-side of precipitation is that it can "clog" the system, reducing permeability in the reservoir to the point where it is no longer possible to inject the $CO_2$.

into geochemical models to predict the evolution of the chemical system over time. This work will need input from the static model and the dynamic models, and will produce results needed for the dynamic model (porosity and permeability changes over time affect injectability of $CO_2$ and where it will go) and the geomechanical model (because precipitation and dissolution will influence rock strength). Results will be important for risk assessment in terms of increased (or decreased) potential for leakage and the potential for the mobilising of certain trace elements released during the dissolution of certain minerals, as well as assessing the times required to reach these potential risks.

### ANALYSIS OF THE INTEGRITY OF EXISTING WELLS

The leakage of $CO_2$ along wells is considered to be one of the most important risks associated with $CO_2$ storage, because wells can form a direct connection between the reservoir and the surface and because $CO_2$ dissolved in water can potentially react with the cements in the well and thus decrease their ability to act as a barrier. Studies have shown, however, that these reactions tend to be very slow, limited by the pace of the dissolution process and the formation of secondary precipitated minerals that block flow. Mechanical or natural stresses can also affect the sealing capacity of a well. Because of these potential risks, the European Storage Directive states that all existing wells which might be in contact with the injected $CO_2$ and future wells required for $CO_2$ storage activity have to be considered in the assessment.

It should be pointed out that if the proposed storage site is a saline aquifer there is a high probability that there will be no deep wells in the area – this excludes one possible leakage pathway, although it also means that there is less underground information for that site. On the other hand if the site is an oil or gas reservoir there is the potential that there may be hundreds of wells in the area.

Wells in the studied area can potentially pass through the caprock and into the reservoir or they may be more shallow; for the sake of risk assessment and site characterisation, only those deep wells in the reservoir are considered. These wells can be either active or abandoned wells. Active wells are typically newer (thus were created with more modern techniques and more stringent regulations), are accessible for repair if necessary, and are being used either for extracting fluids (like oil) or for injecting fluids (like water or $CO_2$). Abandoned wells (or "decommissioned" wells) are closed at the end of their working life by removing the surface pumps and pipes, injecting cement into them to plug them, and then covering them with soil to return the land to its original state. Because these wells would have been closed during different periods in the past, different criteria would have been used; typically wells that were abandoned more recently were done so in a more rigorous way. In addition, as they are eventually covered with soil, in a large, old oil field, the location of all wells can only be determined using records kept by the oil company (or government) or by certain geophysical survey methods.

A well integrity analysis involves measuring, cataloguing and assessing the quality of barriers using cement evaluation documentation and pressure tests. Data on number, age, location, configuration and construction protocols of the wells are also vital. Because of the nature of the abandoned wells, most of the focus and most of the difficulties in finding quality data will be related to their history, design, construction and abandonment materials used, and their performance in the presence of $CO_2$. If it is found that some wells are of high risk they may need to be upgraded, a relatively routine procedure for an active well but a more challenging one for an abandoned well.

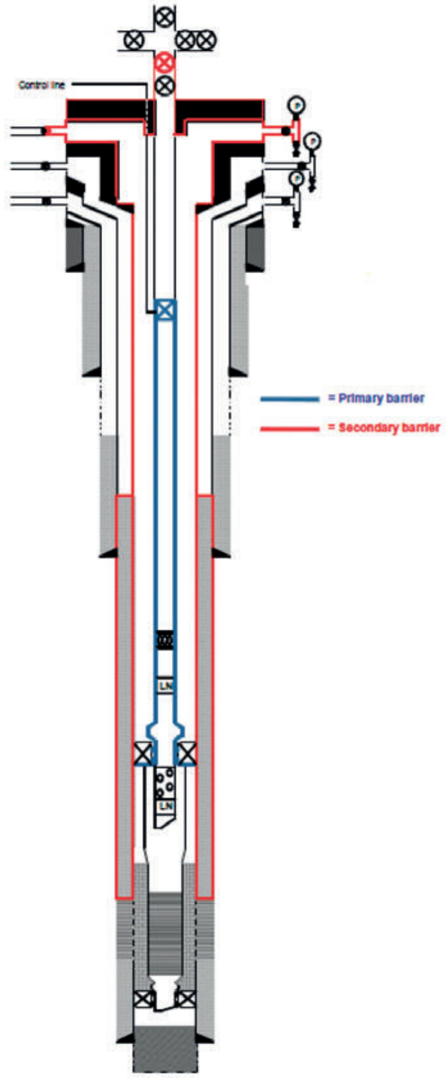
Work in this sector will need information from the static model to understand where the wells are and from the dynamic model to know which wells will actually see the arrival of $CO_2$ and what the pressure conditions will be at that point. Close data exchange is needed between this analysis and the geochemical studies on well cements to assess if a given well is an effective barrier or not. If data gaps exist, this should clearly be stated and ways to reduce these uncertainties should be explored. The outcome of this task describes the potential weak points and associated risks of each of the existing wells in the storage area.

### Analysis of the local geographic and social situation

A process called social site characterisation should be undertaken to understand how the envisaged storage site could be integrated as part of the human activities ongoing in the area. For instance, injector wells can be affected by current land use and the proximity to populated areas. In particular, it will be important to explore, together with the local population, how the proposed project could become part of the local community development, the potential benefits and reasons for its implementation. This will set a good basis for a collaborative relationship between the operator, the local authorities and the population which will help meet the challenges that the realisation of a $CO_2$ storage site can present.

Although the social aspect is not directly addressed in the European Storage Directive, the SiteChar project explicitly included it as an active research topic due to its importance. Through their work in Scotland and Poland the social science researchers used various tools to understand the local socio-economic situation and people's perception about CCS, and they also experimented with new methods to transfer the scientific knowledge to the community so that it can be added to the local discussion and decision making process. In addition to standard interviews, surveys, and information dissemination via the web, so called "focus conferences" were organised as a new form of public outreach. These events brought together project operators, competent authorities, and members of the local public to exchange knowledge, compare opinions, and gain experience in a largely informal setting with lots of space for open discussions. Members of the public

*Fig. 19 - Image of a well highlighting the different barriers: the primary barrier (injection tubing, packer, safety valve) and the secondary barrier (casing, cement outside the casing, wellhead valves).*



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participating in the focus conferences, at the end of two full immersion week-ends, produced a position paper where they expressed their point of view on CCS, formed through the focus conference experience (Polish and Scottish Focus Conference Participants' Position Paper). Over the course of this work it was found that if one truly wants focus conferences that are constructive and useful for all participants it is necessary to have the conference organised by an independent facilitator, to create trust amongst the participants by allowing time for dialogue, to combine the conferences with other public engagement activities, and to make sure that there is a balance of positions taken by speakers and in discussion materials. In real CCS projects, efforts in social site characterisation, information dissemination and raising public awareness, as well as their outcomes, should be embedded in the overall project activities.

## Workflow Phase 4. Full assessment of risks and potential mitigation measures

Once the detailed, complex, and iterative study has been completed and all risks have been studied, tested, and, if possible, reduced by considering various design possibilities, a final decision must be taken about whether this site is safe and viable for geological $CO_2$ storage. This step requires making the risk assessment more quantitative, extending and improving upon the qualitative approach that has been used up to this stage. To accomplish this, all data and models will be used to create a Human, Safety and Environment (HSE) analysis. An HSE involves giving actual numbers to the various risks (as a function of their probability and severity) and comparing these numbers to pre-determined thresholds, and then defining methods for minimising these risks (risk "mitigation"). If the risks are too high compared to the thresholds and the mitigation methods too expensive, the site will be rejected. SiteChar did not address the development of an HSE analysis, as it is a separate, stand-alone activity that occurs after the risk assessment and site characterisation work described here.

## Workflow Phase 5. Final outputs of the site characterisation process preparing for the storage site implementation

If the risk assessment work in both the site characterisation and the Human, Safety and Environment (HSE) analysis show that the site can safely be used for CCS purposes, the results and output from all this work are used to construct a plan to monitor the site (required by the EU Storage Directive) and to create a development and economic plan (required by the operator for project feasibility studies).

### *Monitoring and remediation plan*

Although risks can be minimised, it will probably never be possible to completely eliminate all risks. This is true for CCS just as it is true for any other human endeavour (industrial or otherwise). To address any residual risks and reduce them even further, a monitoring plan must be created and implemented for the site. At this stage the baseline measurements will be completed, to provide the full range of reference values which are necessary for monitoring to be effective. The goals of the monitoring plan will be to ensure that the injected $CO_2$ is behaving as predicted, to look for any unexpected migration or leakage, to determine if any identified leak poses a threat to the environment or human health and to allow corrective actions as soon as possible. The monitoring plan should be flexible, adapting to changing and reducing uncertainties as the project continues and an increasing volume of data is acquired. Monitoring will need to be performed both during injection as well as after the site has been closed and "decommissioned".

A wide range of monitoring tools and techniques exist and have been shown to be effective. The choice of which actual methods to use will depend on the site characteristics, as some methods will give better results in certain environments. Together with the regulator, various issues related to the monitoring program will have to be addressed and decisions made, such as: parameters to be measured; detection limits; maturity and reliability of the techniques; size of area measured; timing and frequency of measurements; etc.

Monitoring plans have been developed within SiteChar for most of the sites. They are in particular a major element of the 2 dry-run permits for the Scottish and the Danish sites.

Should general monitoring indicate an irregularity, detailed and more focussed monitoring will be conducted to confirm its origin. If this additional work determines that leakage is occurring, mitigation or "corrective measures" will be performed to stop the leak

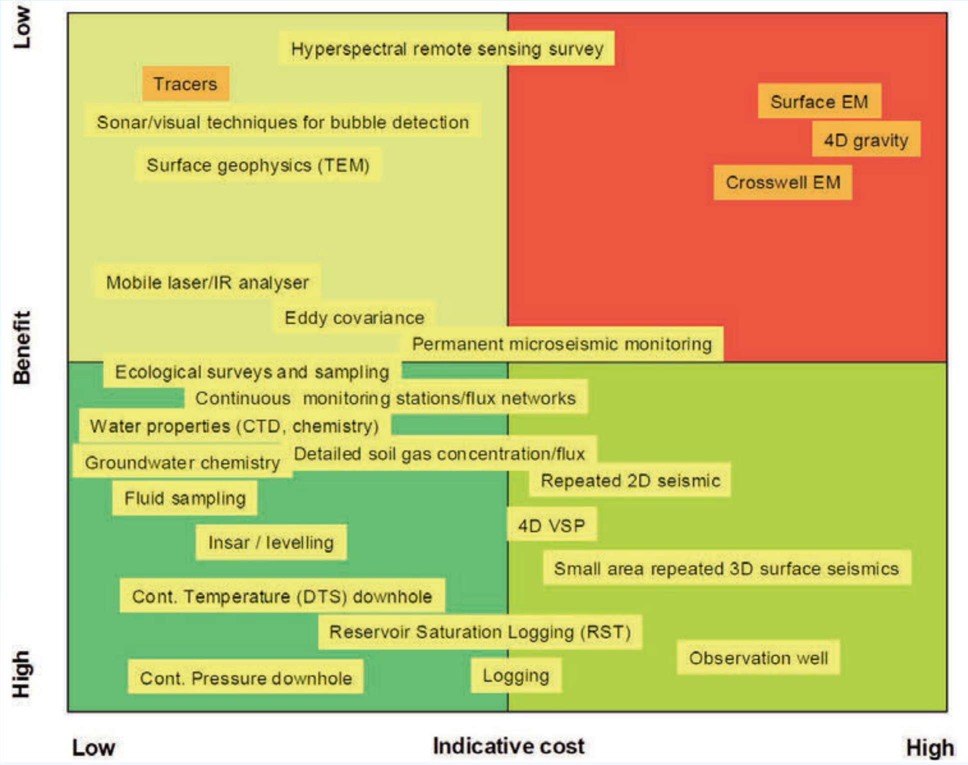


*Fig. 20 - Image from the comprehensive study assessing all relevant monitoring techniques for the Vedsted site ($CO_2$GeoNet).*

and minimise its potential impact. Based on the EC Storage Directive, a corrective measures plan must be created and submitted by the operator during the initial request for a storage permit. Although not a main focus of the SiteChar project, appropriate and feasible corrective measures were proposed within some of the dry-run applications. For example, leakage along an abandoned well could be mitigated by one (or a combination) of the following: stopping $CO_2$ injection and possibly extracting $CO_2$ from the reservoir to decrease pressures, injecting water near the leaking well to create a pressure (hydraulic) barrier and divert flow, or re-working the abandoned well by drilling it out again to seal it properly.

### *Development plan and Economic analysis*

Finally, when the site characterisation study finds no obstacles to secure storage of $CO_2$, a detailed estimate can be made of the work required, and costs, for developing the site for storage. The development plan can be defined on the basis of the injection strategy formulated during the site characterisation process (especially the dynamic modelling) and knowledge of existing installations (if any). The site development plan includes information on the key risks at each step along the process and the decisions involved and provides an estimate of the duration of each of the steps. It is important to realize that these estimates of timing are variable and strongly site dependent. Work within SiteChar showed, for a hypothetical site, that it may take as long as 7 years to develop a saline formation and 6 for a gas field.

## EUROPEAN REGULATION FOR THE GEOLOGICAL STORAGE OF $CO_2$

Sitechar has demonstrated the level of geological characterisation and the assessment of long-term storage complex behaviour in accordance with the regulatory requirements of the **European Directive on the geological storage of $CO_2$**. Information about the state of the transposition of the Eur Directive in Europe can be found at: Rutters, H. and the CGS Europe partners (2013) – **State of Play on $CO_2$ Geological Storage in 28 European countries**. CGS Europe report No. D2.10, June 2013, 89 p.

# PART 3. THE KEY MESSAGES FOR SITECHAR WORKFLOW IMPLEMENTATION

The SiteChar workflow was refined using not only the hands-on experience gained at the five European sites studied during the project itself, but also building upon the extensive knowledge base that has been created over the last 20 years within other EC projects (e.g. GeoCapacity, $CO_2$ReMoVe, $CO_2$GeoNet, etc.), as well as national and industrial research studies. The SiteChar research activities have helped to highlight areas within the workflow where the approach can be made more efficient, more robust, and more effective, thereby creating a site characterisation process that can accurately assess the potential risks of a proposed CCS site. In the end it is hoped that the lessons learned during this project will make CCS safer, thus making it more acceptable, accessible, and economically feasible. Some of the more important observations are summarised below.

The team that conducts a site characterisation study must be formed by people with a **wide range of different technical capabilities** ("multi-disciplinary") to ensure that the project has been considered from all angles and that the eventual storage site will truly be safe and secure. Communication between these various disciplines must be a priority.

**Progress and outcomes of technical site characterisation should be shared with the local community**. Local authorities and civil society organisations should be actively involved in the initial qualitative risk assessment process to ensure transparency and to show that all potential risks have been studied in a rigorous and unbiased manner.

**Site characterisation is an iterative process**, meaning that each method produces data that is needed by the other methods to improve their estimates and simulations. This exchange of results must take place at numerous points throughout the site characterisation process so that the models become progressively less qualitative and more quantitative, in other words they give a more accurate measure of the real world.

**Site characterisation is risk-based**, meaning that the focus of the entire process is to define risks and to look into design features and site settings that can minimise any risks.

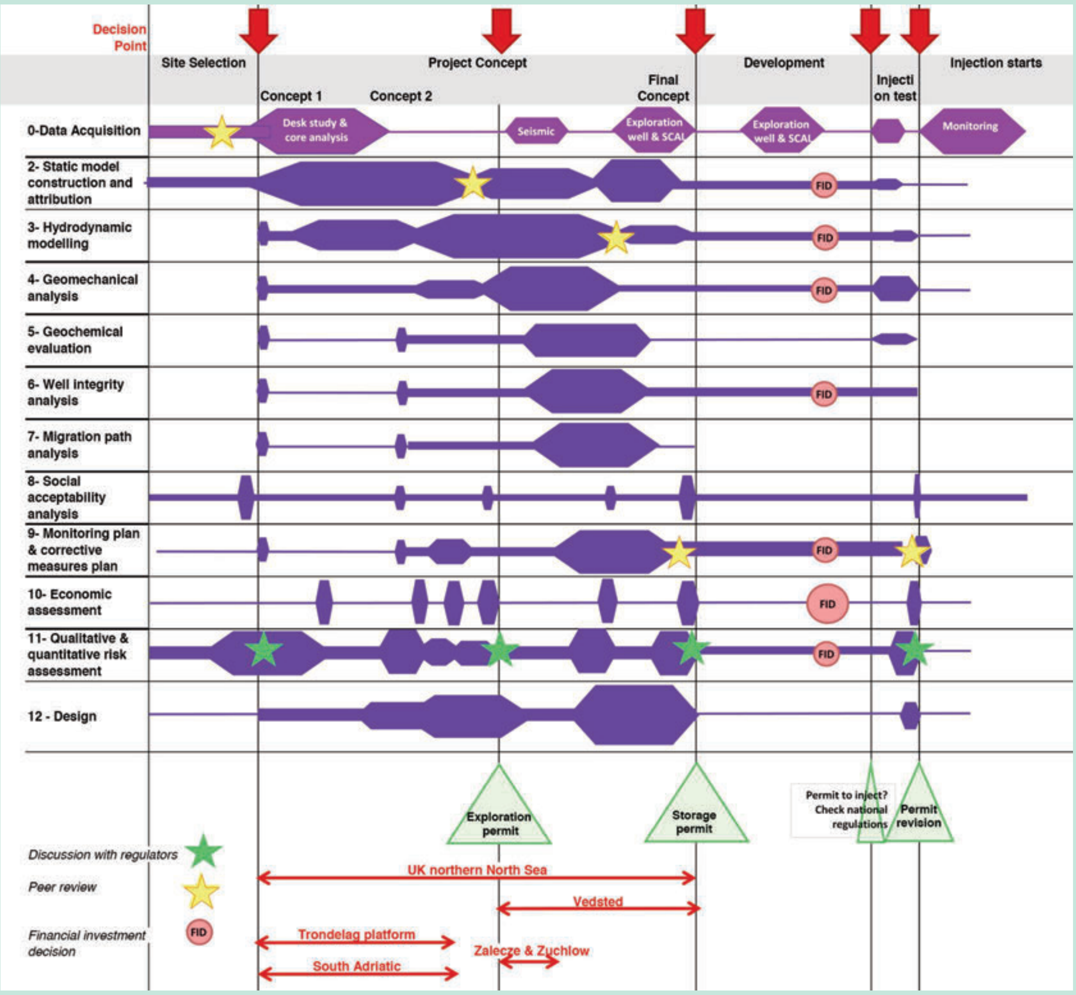
**Regular, continuous contact is needed between the operator and regulator teams**, to ensure that the correct type and amount of data is collected, and that the types and quality of the model simulations are sufficient to satisfy the stringent regulations. The regulator has great authority over site selection, characterisation, and monitoring, and thus needs the tools and information to make the best decisions.

**Every potential site is unique.** Because of this the Workflow is a road map, not a recipe from a cookbook. It highlights the general approach and tools needed, but details will be decided based on the site and the regulator.

# SITECHAR BEST PRACTICES AND GUIDELINES

The knowledge outcome of the SiteChar project is brought together for the benefit of operators and regulators in the final deliverable D2.4 Best Practices and Guidelines developed from the SiteChar project. The content of this report includes indications regarding the possible structure of a permit application and its development based on the SiteChar experience. It also formulates recommendations and provides suggestions for the improvement of the European regulatory framework.

**The concept: focused and risk-based site characterisation.** SiteChar recommends that site characterisation should be driven by risk and uncertainty assessment, aiming to anticipate, reduce and mitigate risks and identify objectives for subsequent storage performance monitoring. This requires the Competent Authority and operator to share a common understanding of the site and the storage project. As part of this, practical approaches to defining the storage complex have been developed within SiteChar.



*SiteChar workflow recommended process.*

*This is a schematic timeline, the height of the different boxes roughly indicating the amount of work required for each step of the workflow.*

**SiteChar exemplar storage permit application.** SiteChar has developed a "dry-run" storage permit applications at the Scottish and Danish sites. The review of these applications and the lessons learnt will help regulatory authorities to identify the necessary levels of evidence required to assess the safety, containment and storage capacity of putative sites. SiteChar recommendations will enable operators to directly address key issues for cost efficient and effective storage permit applications.

**Contribution for the improvement of the EC Storage Directive.** Recommendations are made 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.

**Recommendations for the long term safety of storage sites.** Firstly, establishing agreement during the permit process of the level of evidence required to demonstrate permanent safe containment will be a significant aspect of site characterisation activities. In addition to successfully obtaining a permit to store, this agreement will also enable the transfer of the site to the State at the end of the project. This transfer will be planned from the beginning and prepared for throughout the CCS project. Both operators and Competent Authorities will need certainty on the metrics by which the site performance will be assessed and by which safe, permanent containment will be demonstrated.

Secondly, managing uncertainty and conveying the level of confidence accurately without undermining safety require further attention. All predictions of site performance will carry a level of confidence and uncertainty. It will be important for Competent Authorities and operators to agree on the levels of acceptable uncertainty. Operators will need to develop a plan for uncertainty reduction during the process of operating the site, supported by an adequate baseline site characterisation and an appropriate program of site monitoring. Definition of acceptance criteria is the key to determine the level of required evidence to gain a storage permit, allowing both operator and regulator to demonstrate safe performance, both during the operational and closure phases and providing a basis for the design of the geological monitoring program and the corrective measures plan.

**Recommendations for authorities.** Governments set national policies and local authorities may contribute to their implementation through local policy development and the planning process. $CO_2$ storage projects could therefore form a component of the discussions about the approaches to sustainable energy supply as well as use of the subsurface. Furthermore, assessing interactions with other users is a key consideration for regulators but this might be challenging for operators since such an assessment requires an overview of relevant future uses of the underground. Management of the pore space is also a strategic issue that requires both operators and relevant authorities to consider the efficient use of the pore space in the selection and operation of sites.

## Short glossary

**$CO_2$ plume**: spatial distribution of the $CO_2$ within the rocks.

**$CO_2$ flux**: the quantity of $CO_2$ released by the soil (in a given time, for a given area, usually grams per square meter per day).

**Caprock**: impermeable layer of rocks that acts as a barrier to the movement of liquids and gases and which forms a trap when overlying a reservoir.

**Fault**: in geology a natural break in the rocks, resulting in the displacement of one side relative to the other. This displacement may be lateral, vertical or a combination of both.

**Focus conference**: a participation method involving a small group of local citizens. The focus conference method structures participation in two weekends combining provision of expert knowledge with lots of room for discussions, allowing each participant to gain their own experiences with the topic and creating opportunities for comparing their own opinion with the opinion of others.

**Fracture**: a break in rock along which no significant displacement has occurred.

**Modelling**: gaining information about how something will behave, for instance using computer simulation, before testing it in real life. Geologic modelling is the applied science of creating computerized representations of portions of the Earth’s crust based on geophysical and geological observations made on and below the Earth’s surface.

**Porosity**: percentage of the volume of a rock that is not occupied by mineral. The gaps are pores and may be filled with various fluids such as salt water, oil, methane, or $CO_2$.

**Permeability:** the ability of a rock to transmit fluid through the pore spaces. In $CO_2$ geological storage, it refers for instance to the ability of a porous rock, such as sandstone, which acts like a sponge to allow the injected $CO_2$ to fill the tiny spaces between grains of the rock.

**Social site characterisation**: the process of making a “social map” of the area concerned with a potential $CO_2$ storage site, identifying who are the stakeholders, what factors shape their perception of CCS and what are the socio-economic, political and cultural characteristics of the area. Methods include desk research, interviews, media analyses and surveys. Social site characterisation runs as a parallel activity to technical site characterisation. It is useful to screen out unsuitable sites and to help design the storage project to address site specific conditions.

**Soil gas concentration**: the percentage of $CO_2$ and other gases (like oxygen, helium, methane, etc.) present in the soil's pore space air.

## LINKS

A Roadmap for moving to a competitive low carbon economy in 2050
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0112:EN:NOT

European Parliament resolution on CCS of 14 January 2014
http://www.europarl.europa.eu/sides/getDoc.do?type=REPORT&reference=A7-2013-0430&language=EN

International Energy Agency CCS Roadmap
http://www.iea.org/publications/freepublications/publication/CCS_roadmap_foldout.pdf

Energy 2020 - A strategy for competitive, sustainable and secure energy
http://ec.europa.eu/energy/strategies/2010/2020_en.htm

A Roadmap for moving to a competitive low carbon economy in 2050
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52011DC0112:EN:NOT

2009/31/EC Directive on the geological storage of carbon dioxide
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:32009L0031:en:NOT

"State of play on $CO_2$ geological storage in 28 European countries"
http://www.cgseurope.net/Sections.aspx?section=517.537

SiteChar technical brochure
http://www.sitechar-co2.eu/SciPublicationsData.aspx?IdPublication=321&IdType=557

D2.1 Synthesis and lessons learned from the application of the SiteChar workflow
http://www.sitechar-co2.eu/SciPublicationsData.aspx?IdPublication=324&IdType=557

D2.4 Best practices and Guidelines developed from the SiteChar project
http://www.sitechar-co2.eu/SciPublicationsData.aspx?IdPublication=325&IdType=557

D8.5 Final summary report on public awareness
http://www.sitechar-co2.eu/SciPublicationsData.aspx?IdPublication=327&IdType=557

Polish and Scottish Focus Conference Participants' Position Paper
http://www.sitechar-co2.eu/SciPublicationsData.aspx?IdPublication=299&IdType=557

European Directive on the geological storage of CO2State of Play on CO2 Geological Storage in 28 European countries
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:140:0114:0135:EN:PDF

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The deep underground storage of man-made carbon dioxide ($CO_2$) has been recommended as an important tool, together with many others, to reduce the greenhouse effect and slow down climate change. Although the technology to do this has been used for over 40 years in the oil and gas industry, and despite the fact that some $CO_2$ storage projects already exist, the general public is often hesitant to fully support this approach due to concerns about safety. The SiteChar project, which has been funded by the European Community, has tried to address these concerns by developing a road map which can be used to help government regulators and site operators select the safest sites and minimise any risks to human health or impact on the environment. Using proven technologies, scientists and engineers build on and integrate results from each other's work to test sites for their appropriateness, making sure that they meet the stringent requirements outlined in the various European directives and national laws that govern $CO_2$ storage. This document gives a broad overview of the approach developed within the project, in the hopes of stimulating interest (and debate) in a technique that can potentially give an important contribution to combating man-made climate change.

http://www.sitechar.eu