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Abstract

This document is deliverable D26 the work package report of WP4 Capacity standards and site selection criteria in the EU GeoCapacity project and provide a summary of the work carried out in WP4.1 Site selection criteria and WP4.2 Storage capacity standards.

The objective of WP4.1 is to produce a set of site selection criteria required when considering sites for geological storage and to develop a site ranking methodology. The basic selection criteria, geological parameters and important ranking criteria have been outlined in the report D23 Site selection criteria. The criteria have been applied by GeoCapacity partners when selecting sites and can serve to standardize other projects and future work. Ranking methodology and application of the methodology to a test case study have been described in the report D25 Application of standards.

The objective of WP4.2 is development of methodologies for calculating storage capacity in different geological settings and application of the standards to a test area. A standardized methodology for storage capacity estimation in aquifers, hydrocarbon and coal fields have been outlined in the report D24 Storage capacity standards. The standards have been applied by GeoCapacity partners when estimating storage capacity and can be applied to other projects and future work as well. Application of the standards to a test area and sensitivity analyses of change in storage capacity based on different methodology have been described in the report D25 Application of standards.

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1 INTRODUCTION

The focus of the GeoCapacity project is GIS mapping of CO_2 point sources, infrastructure and geological storage in Europe. The main objective is to assess the European capacity for geological storage of CO_2 in deep saline aquifers, oil and gas structures and coal beds. Other priorities are further development of methods for capacity assessment, economic modelling and site selection as well as international cooperation, especially with China. The results of GeoCapacity include 25 countries and comprise most European sedimentary basins suitable for geological storage of CO_2.

The Work in GeoCapacity has been structured in 7 work packages:

- WP1: Inventory of emissions and infrastructure, GIS
- WP2: Storage capacity
- WP3: Economic use of CO_2
- WP4: Capacity standards and site selection criteria
- WP5: Economic evaluations
- WP6: International cooperation
- WP7: Project management

This document is deliverable D26 the work package report of WP4 Capacity standards and site selection criteria in the EU GeoCapacity project and provides a summary of the work carried out in WP4.1 Site selection criteria and WP4.2 Storage capacity standards.

The objective of WP4.1 is to produce a set of site selection criteria required when considering sites for geological storage and to develop a site ranking methodology based on geological suitability for CO_2 storage and on data availability and confidence. The basic selection criteria, geological parameters and important ranking criteria have been outlined in the report D23 Site selection criteria (Vosgerau et al., 2008). The criteria have been applied by GeoCapacity partners when selecting sites ensuring quality and consistency and can serve to standardize other projects and future work. Ranking methodology and application of the methodology to a test case study have been described in the report D25 Application of standards (Vangkilde-Pedersen et al., 2008).

The objective of WP4.2 is development of methodologies for calculating storage capacity in different geological settings and application of the standards to a test area using GESTCO experience and referring to other international projects (US and Australian). A standardized methodology for storage capacity estimation in aquifers, hydrocarbon and coal fields have been outlined in the report D24 Storage capacity standards (Vangkilde-Pedersen et al., 2008). The standards have been applied by GeoCapacity partners when estimating storage capacity ensuring quality, consistency and comparability and can be applied to other projects and future work as well. Application of the standards to a test area and sensitivity analysis of change in storage capacity based on different methodology have been described in the report D25 Application of standards (Vangkilde-Pedersen et al., 2008).

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2 SITE SELECTION

For a site to be suitable for CO_2 storage some basic, geological related criteria has to be fulfilled. These are,

1. Sufficient **depth of reservoir** to ensure that CO_2 reaches its supercritical dense phase but not so deep that permeability and porosity are too low.
2. **Integrity of seal** to prevent migration of CO_2 from the storage site.
3. Sufficient CO_2 **storage capacity** to receive the CO_2 expected to be released from the source.
4. Effective **petrophysic reservoir properties** to ensure CO_2 injectivity to be economically viable and that sufficient CO_2 will be retained.

Fulfillment of these basic criteria depends on the values of several geological and physical parameters. In the search for suitable sites for CO_2 storage it is therefore important to estimate if the basic criteria listed above and their associated geological and physical parameters are fulfilled. The first step in a site selection process is to screen sedimentary basins for CO_2 storage potential. The goal with the screening process is to identify predictable, laterally continuous, permeable reservoir rocks overlain by potentially good quality caprocks at a suitable depth. By screening, an overview is obtained of those sites which are best described and fulfill the storage criteria on the basis of existing data. The screening therefore narrows the search at an early stage so that costly and time-consuming supplementary investigations such as collecting and interpreting seismic data are confined to small prospective areas.

Structures which do not satisfy one or more of the criteria in the screening process should be initially excluded. However, those structures should not be totally ruled out as storage sites, detailed site-specific studies are needed in order to prove their ability to store CO_2.

If several, equally suitable CO_2 sites are identified in the screening process other non-geological criteria such as economic, logistical and conflict of interest considerations may be used to decide which of those sites shall be investigated in more detail. For example the proximity to the CO_2 source may be highly valued based on economic considerations (short pipeline route). A potential CO_2 storage site may be excluded if there are conflicts of interest. For example deep aquifers with high porosity for CO_2 storage would also be potentially suitable for geothermal energy production or they may form strategic reserves for storage of natural gas.

Once the most well suited site(s) is/are chosen based on existing data, it should be evaluated with supplementary geological information which would need to be collected to ensure that the site is in fact is suitable for CO_2 storage.

The following section focuses on the geological and physical parameters in the initial screening of suitable CO_2 storage sites. The geological parameters and their impact on the basic criteria mentioned above are described and recommended values are given for those parameters which generally are most accessible and considered most important in the screening phase.

Supplementary investigations of potential CO_2 storage sites, pointed out in the screening phase, are beyond the scope of this report. Guidelines for detailed site characterization procedures are given in Chadwick et al. (2006).

3 DESCRIPTION OF BASIC SITE SELECTION CRITERIA

In this section the basic site criteria, depth of reservoir, petrophysic reservoir properties, integrity of seal and storage capacity, are described together with their associated geological and physical parameters.

3.1 Depth of reservoir

The density of CO_2-rich gasses increases with depth as a result of increasing temperature and pressure. Under normal reservoir conditions there is a steep increase in the density with an associated decrease in the volume of CO_2 at depths between 600-800 metres (Figure 1). This is dependant on the geothermal conditions and pressure of the formation in question. At depths of more than 800 metres (~ 8 MPa pressure) the CO_2 will be in its dense (liquid or supercritical) phase, at depths less than this it will be in its gas phase and not dense enough for storage to be economically viable. For this reason storage is recommended in formations that lie at depths of 800 metres or deeper.

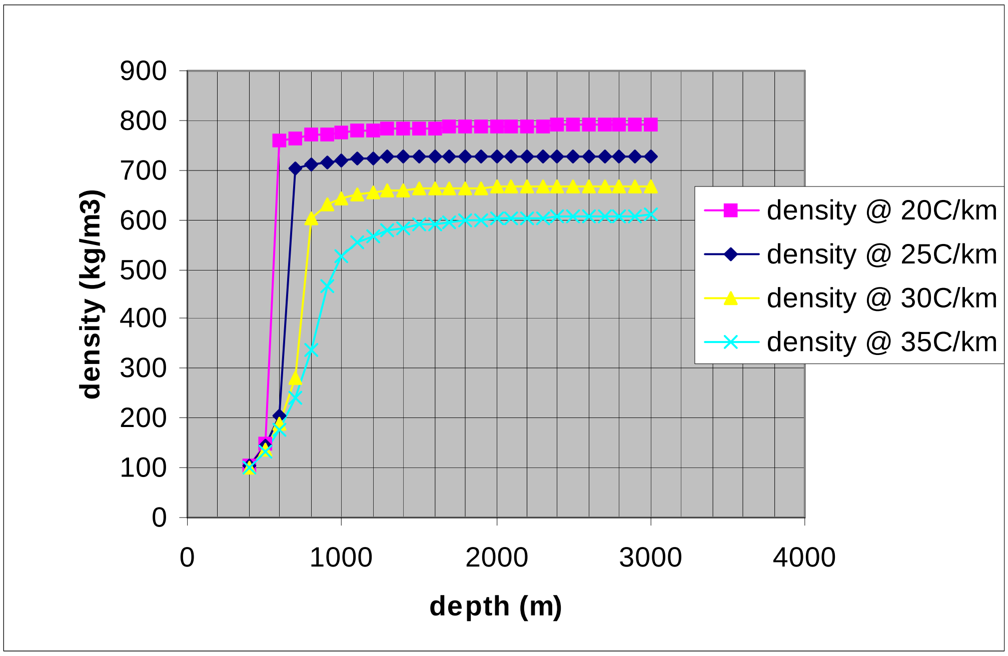

Figure 1: Density of CO_2 at hydrostatic pressure and typical geothermal gradients.

Impurities in the CO_2-rich gasses have a negative effect on the decompaction rate of the gas with depth and it may therefore be necessary to include this aspect when a minimum depth of the reservoir is considered (Figure 2).

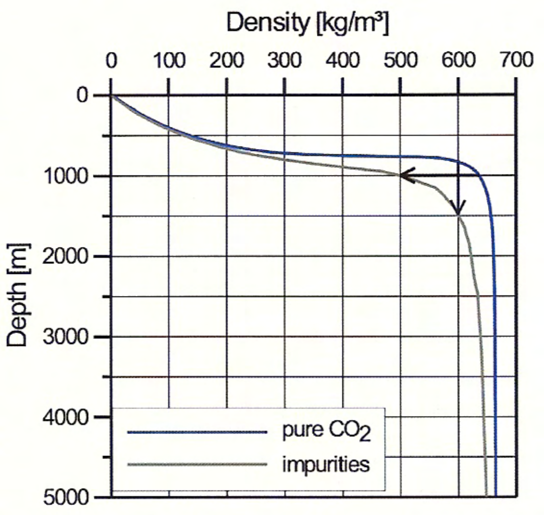

Figure 2: The effect of impurities (2.75% O_2 and other components) on CO_2 density variation with depth. From Chadwick et al. (2006).

However, with increasing depth the permeability and porosity of the sandstone reservoir normally decrease due to digenetic alterations. This has a negative effect on the CO_2 storage capacity of the reservoir and the ability to inject CO_2 into the reservoir as described below under petrophysic reservoir properties. For this reason it is recommended as a rule of thumb that the storage depth is not greater than 2500 metres unless well data are present to validate acceptable porosity and permeability values at greater depth (Chadwick et al., 2006).

3.2 Petrophysic reservoir properties

A reservoir must have some basal petrophysic properties to be suitable for CO_2 storage. The basic parameters are the permeability and the porosity. High permeability values ensure that it is easy to inject CO_2 into the reservoir and high porosity values ensure that there is pore space available for the CO_2 storage. The parameters are explained in more details below.

3.2.1 Permeability

Permeability is a measure of the ability of a material to transmit fluids. In the case of CO_2 storage the material typically is a rock of sedimentary origin. The permeability is of great importance in determining the flow characteristics of the injected carbon dioxide in the reservoir. Permeability is commonly symbolized as κ, or k. The unit used for describing permeability is the millidarcy (mD); (1 darcy $10{-}12\text{m}^2$).
Permeability needs to be measured, either directly (using Darcy's law) or through estimation using empirically derived formulas. As a general rule of thumb the formation permeability must exceed 200 mD for a specific reservoir to provide sufficient injectivity (van der Meer, L.G.H. 1993). However, values greater than 300 mD are preferred (Table 1).

3.2.2 Porosity

Porosity is a measure of the relative volume of void space in a rock to the total rock volume. The void may contain, for example, air, water or hydrocarbons. Porosity is measured as a fraction, between 0–1, or as a percent between 0 - 100%. Effective porosity (also called open porosity) refers to the fraction of the total volume in which fluid flow is effectively taking place (this excludes dead-end pores or non-connected cavities). These spaces or pores are in the juvenile state water bearing and in the case of petroleum findings where oil and gas accumulate. Therefore, a high effective porosity promotes the amount of CO_2 to be stored. The fraction (by volume) of a reservoirs pore space that can be filled by CO_2 (in free or dissolved form) is called the storage efficiency. In the case of natural gas storage in aquifers, a bulk gas saturation of more than 50 vol.-% may be reached. For trap structures, the ability to displace pore fluids from within the trap to surrounding reservoir rocks will govern the value of the storage efficiency (see below). Making use of several injection wells facilitates efficient storage. According to numerical case studies, less injection effort would result in lower mean saturations.

As a general rule of thumb porosities should be larger than 20 % (Chadwick et al., 2006). Porosities below 10% are cautionary.

3.3 Integrity of seal

Given the buoyant nature of CO_2 a reservoir must have an overlying seal/cap rock to be able to store CO_2 effectively. Typical formations with good sealing properties are rocks with low permeability such as lacustrine and marine mudstones, evaporates and carbonates. The integrity of the seal is governed by the thickness of the sealing formation, the absence of faults crossing the formation as well as the impact of geochemical interactions between CO_2 and the caprock. Parameters that influence the properties of a caprock are described below.

3.3.1 Permeability

Permeability is a measure of the ability of a material to transmit fluids and in the case of a seal the permeability should therefore be as low as possible thereby hindering the transport of CO_2 through the matrix of the caprock. The parameter is described in more details under ‘Petrophysic reservoir properties’ above.

3.3.2 Seal thickness

A thick seal naturally has a positive effect in preventing the leakage of CO_2 from a reservoir. A thickness less than 20 metres is cautionary whereas thickness greater than 100 metres is preferable (Chadwick et al., 2006).

3.3.3 Faults

Faults may have several, partly opposing effects on the migration of CO_2. Sealing faults can constitute traps, thereby both trapping CO_2 and constraining its migration pathways. Non-sealing faults in contrast may enable the CO_2 to escape through the seal along faults and thereby potentially escape to the seabed or the atmosphere. Seal integrity may also be compromised by hydrofracturing the cap rock, which occurs when the pore pressure of the reservoir is the same as the least principal stress in the overlying unit (Chiaramonte et al., 2006).

3.3.4 Tectonic activity

To avoid a sudden escape of pressurised CO_2 along faults, storage sites should not be in an area of recent seismic or tectonic activity. Pressurised CO_2 ascending along faults could expand rapidly at sub-critical conditions, reducing the fault strength and opening up pathways for the gas to escape to the surface. The injection of large quantities of CO_2 may also change the local stress field, and thus trigger seismicity. Statistics on seismic activity should therefore be checked for potential storage sites.

3.3.5 Heterogeneity of seal

A homogeneous, low permeable seal inhibits the migration of CO_2 through the seal. Abundance of homogeneity, such as sandstone beds and lenses in a seal of mudstone, increases the risk of CO_2 leakage as the sandstone occurrences may be connected directly or by small faults, thereby forming migration pathways for the CO_2.

3.3.6 Geochemical interactions

Once CO_2 dissolves into water it forms carbonic acid. This acidifies the formation water and potentially attacks and alters the cap rock and fractures within the cap rock. These chemical interactions might change the physical characteristics of part of the seal and thus potentially enhance CO_2 migration towards the surface.

3.4 Storage capacity

All identified storage sites should be capable of storing the lifetime emissions of the selected point source(s). With respect to power plants the nominal plant lifetimes are approximately 20 - 30 years. If a coal-fired power plant has annual CO_2 emissions of 4 million tonnes (Mt) then the storage site should consequently have a minimum capacity of 80 Mt available for utilization. Lifetimes will vary according to different types of industry. As a general rule of thumb the estimated total storage capacity of a reservoir should be much larger than the total amount from the CO_2 source.

Geological parameters, which influence the storage capacity, include trap type, occurrence of faults, heterogeneity of the reservoir, thickness and areal extent of the reservoir as described below. In addition, the petrophysic properties of the reservoir naturally also have a large effect on the storage capacity as described above.

3.4.1 Trap type

CO_2 storage capacity depends not only on the properties of the reservoir itself but also on the nature of its boundaries. As described in Chadwick et al. (2006) very little CO_2 can be injected into the water filled porosity of a small reservoir with perfectly sealed non-elastic boundaries, as the only space available will be that created by the compression of the water and rock. Furthermore, this may result in an unacceptable rise in reservoir pressure towards the seal implying that CO_2 may leak through and along micro-fractures or faults or by migration through the matrix of the seal if the pressure overrides the capillary entry pressure of the seal.

For significant storage it is therefore necessary that a large proportion of the native pore fluid is displaced from the reservoir over the injection period. This may occur either by anthropogenic production of fluids (oil and gas), by deliberate production of formation water, or by formation water displacement to the surrounding aquifer by the injected CO_2. Aquifers, in which formation water is expelled by injected CO_2, may be divided into aquifer traps and regional aquifers, as described below.

Aquifer traps
The majority of suitable structures that can keep CO_2 over long periods of time consist of a three-dimensional structural closure forming different trap types. The ideal convex structure is an isolated dome that dips in all directions radially away from the central high. All kinds of different shapes of closures occur naturally, from circular to elongate to complex. A common denominator is, however, that they will be terminated upwards by a highest point that can be

measured directly (wells) or indirectly (seismic profiles) as depth to the crest of the structure. In case of complex shaped closures several crests may be present. Large structures naturally provide larger storage capacity compared to minor structures. The more well-defined the structure is the more control there is on volume estimates of the aquifer due to the predictable trapping geometries.

Regional aquifers

CO_2 storage may also take place in regional dipping aquifers as described in Chadwick et al. (2006). The seals above these aquifers are also dipping and may be incomplete; they would inhibit direct vertical migration of the injected CO_2 and deflect the migration path to a near horizontal course, but they would not hold the CO_2 permanently *in situ*. Ultimately the CO_2 would likely reach a non-sealed part of the reservoir and escape into the ocean and eventually the atmosphere if it were not kept within the reservoir by counteracting processes. Such processes that have an effect at relevant timescales (100s to 1000s of years) are dissolution into formation water and residual gas trapping due to relative permeability hysteresis. Regional dipping aquifers may therefore provide effective CO_2 storage options if the above mentioned processes operate and there is an adequate distance between injection wells and potential leakage points.

3.4.2 Heterogenity and faults

Internal barriers within the reservoir, such as faults or lithological heterogeneity, need to be considered as these may divide the reservoir into separate, unconnected or poorly connected compartments which may behave independently of one another. It is therefore easier to estimate the CO_2 storage capacity for non faulted reservoirs with a homogeneous lithology compared to reservoirs which are heavily faulted and strongly heterogeneous. Furthermore, in the latter type of reservoirs the injection of CO_2 may require at least one well per compartment (Kirk, 2006) and the dispersal pattern of the injected CO_2 is more difficult to predict. On the other hand, lithological heterogeneity may promote additional fixing processes of CO_2 within the reservoir in addition to the structural trapping. Intra-reservoir heterogeneity is therefore likely to increase effective storage capacity in the longer-term by encouraging dissolution of CO_2 into the formation water, promoting 'stratigraphical' trapping of CO_2 as an immobile residual phase and promoting geochemical reaction leading to chemical 'fixing' (Chadwick et al., 2006).

Knowledge of the depositional environment of the reservoir sandstones may give a hint of the lithological heterogeneity. For instance, intercalated mudstone is generally more common in sandstone deposited in a meandering river system compared to sandstone deposited in a braided river system.

3.4.3 Thickness and areal extent

The size of the CO_2 storage structure will be defined by the last closing contour at a certain depth. Beneath that depth the CO_2 will not be contained within the structure and be allowed to spread uncontrollably. The areal extent of a CO_2 storage site will have impact on the surface area, the so called 'footprint', which will have to be included in further investigations once a storage site is planned.

Reservoirs of less than 20 m of cumulative thickness of good reservoir sandstone beds are thought not to be suitable for the storage of large amounts of CO_2 (Chadwick et al., 2006). As a generally rule of thumb the thickness should be larger than 50 metres. Naturally, a small thickness can be compensated by a large areal extent of the reservoir. This however, also implies a large ‘footprint’ area, making eventual monitoring of CO_2 leakage to the surface more complicated and expensive. In addition it requires a large area to be mapped in detail to identify potential leakage pathways (particularly faults). Information on the probable areal extent of a ‘footprint’ can be estimated with the help of geological maps and geological cross sections. Geological maps of the deep surface and seismic profiles will help to define the extent of the structure in more detail, as well as depth structure map displaying the geological succession of interest if existent. Geological maps may also give information of the occurrence of possible faults.

3.4.4 Other parameters with implication on the storage capacity

Apart from the above mentioned parameters the CO_2 volumes that can be stored in aquifers depend on many poorly-determined parameters and issues as described in Chadwick et al. (2006), including:

- Residual saturation trapping, in which capillary forces and adsorption onto the surfaces of mineral grains within the rock matrix immobilise a proportion of the injected CO_2 along its migration path.
- Geochemical trapping, in which dissolved CO_2 reacts with the native pore fluid and the minerals making up the rock matrix of the reservoir. CO_2 is incorporated into the reaction products as solid carbonate minerals and aqueous complexes dissolved in the formation water.
- The amount of CO_2 that will dissolve into the saline pore fluids.

4 THE SCREENING PROCESS

The basic parameter values in pointing out potential CO_2 storage sites in the screening process are listed in Table 1. The parameter values are used as general rules of thumbs based on knowledge obtained from several case studies and knowledge from the petroleum industry (Chadwick et al., 2006). As exact parameter values are commonly lacking in the screening process it may be necessary to use derivative parameter values. For example as petrophysic parameter values may not be present in the screening process, a reservoir depth less than 2500 meters is used as screening criteria to most likely ensure suitable porosity and permeability values in the reservoir. In addition, the lithology of the reservoir and cap rocks indirectly reflects porosity and permeability values. The inferred parameter values have to be verified in the detailed site description which follows the screening process.

Table 1: Key geological indicators for storage site suitability. Based on Chadwick et al. (2006).

Basic, geological related criteria	**Influential geological and physical parameters**	**Criteria to investigate in the screening process**	
		Positive indicators	Cautionary indicators
Sufficient depth of reservoir	Pressure Temperature Porosity Permeability	Depth of crest of reservoir > 1000 m. Depth of base of reservoir < 2500 m.	Depth of crest of reservoir < 800 m. Depth of base of reservoir > 2500 m.
Petrophysic reservoir properties	Porosity	> 20%	< 10%
	Permeability	> 300mD	<200 mD
Integrity of seal	Lithology	Low permeable lithologies, such as clay	
	Porosity Permeability		
	Thickness	> 100 m	< 20 m
	Faults	Unfaulted	Faulted
	Heterogeneity	Homegenous	Heterogeneous
	Tectonic activity	No tectonic activity	Tectonic activity
Storage capacity	Reservoir:	Total capacity of reservoir estimated to be much larger than the total amount produced from the CO_2 source.	Total capacity of reservoir estimated to be similar to or less than the total amount produced from the CO_2 source.
	Thickness	> 50 m	< 20m
	Areal extent	Well defined	Not well defined
	Heterogeneity		
	Faults	Unfaulted	Faulted
	Trap type	Well defined structures	Not well defined
	Petrophysic prop.	Values given above	Values given above

To which degree it is possible to characterize and evaluate the potential storage sites in the screening phase naturally depends on how much relevant data there are available and the knowledge of the geological development of the region in question (e.g. stratigraphic units, lithology, depositional paleoenvionment, burial history). Geological information can be reviewed using maps or geological literature. More detailed information is available from wells or seismic data which, however, often are property of exploration companies and therefore may not be available. Prospects identified in areas with few wells and petroleum discoveries (or other commercial investigations such as geothermal and gas storage) are difficult to develop to the level of confidence, because of a lack of geological and reservoir engineering data or near gas-tight structures that could be used as analogies (Chadwick et al., 2006).

A large knowledge based on existing data implies that it is possible to make a well qualified choice of suitable sites in the screening process and that the amount of supplementary investigations that follow for site characterization may be less comprehensive. In contrast, if existing data are limited in the screening process this probably results in several potential storage sites which need to be investigated further before the most suitable site can be chosen. As it can be very expensive to produce the necessary data from several sites it may be appropriate to investigate the sites one by one until a suitable site is found. The order in which the sites should be investigated could then be determined by non-geological criteria. For example, it may be appropriate first to investigate the site which is closest to the CO_2 source, thereby keeping the installation costs down (short pipeline) if the investigations show that the site is suitable for CO_2 storage.

If the amount of geological data is limited at the potential storage site, nearby, geologically well described regions may be used as analogues under the assumption that they are the same lithostratigraphic units of interest which occur at the potential storage site. In that case it is appropriate to produce a geological model in order to assess if data from the analogue can be used directly or if variations must be incorporated due to differences in thickness, heterogeneity and petrophysic properties of the reservoir and seal formations.

5 RANKING METHODOLOGY

The criteria for ranking storage sites have been developed in the framework of WP4.1 at the GeoCapacity meeting in Athens in spring 2007. In this section, the criteria list is applied to a test case study near the Polish-German border.

In the area of Szczecin there are several industrial CO_2 sources and four nearby potential storage sites. The four storage sites are evaluated and ranked using the defined criteria.

5.1 Methodology

The criteria to evaluate and rank storage sites are listed in

Table 2. They are the result of joint discussions and assessment by scientists from BGS, GEUS, TNO, BRGM, IFP, Vattenfall AB, and BGR.

To assess the data availability and quality the site selection criteria and geological parameters of

Table 2 have been weighted qualitatively as shown in Table 3. The result of the application of the weighting to the four storage sites can be found in Table 5.

5.2 Test case study

In and around Szczecin there are several industrial CO_2 sources in the form of several power plants, a heating plant, a chemical plant, a steel plant, and on the German side of the border another planned power plant and a refinery. In 2004 the emissions from these facilities were about 10.3 Mt CO_2 (Table 4).

In the area four geological structures with a potential for CO_2 storage have been identified:

- Greifswalder Bodden (Germany)
- Kamien Pomorski (Poland)
- Loecknitz (Germany)
- Chabowo (Poland)

Three of the sites are within about 60 km of Szczecin and the fourth, Greifswalder Bodden, is about 120 km north-west of Szczecin. Three of the sites are saline aquifers, and one, Kamien Pomorski, is a depleted oil field. The two Polish storage sites are described as case studies in the framework of the GeoCapacity project. The site Greifswalder Bodden was described as a case study in the GESTCO project. Only one site, Loecknitz, has not been described in the framework of an EU project and because of this published data are rather scarce.

The industrial CO_2 sources and potential storage sites are shown in Figure 3.

Table 2: Site selection criteria, WP4.1.

Basic site selection criteria	sufficient depth for supercritical dense phase (> 800 m) sufficient injectivity to be economically viable integrity of seal in terms of faults/capillary pressure
Geological parameters	permeability (max-min) porosity (max-min) depth to crest (max-min) depth to base of reservoir (max-min) reservoir lithology type seal lithology type seal permeability seal capillary pressure seal pore entry pressure (can estimate if permeability is known) faulting in seal heterogeneity of system storage type (e.g. hydrocarbon field/aquifer) trap type pressure temperature tectonically active thickness of reservoir (min-max) areal extent pore volume fracture pressure availability of data conflicts of interest
Ranking criteria	depth injectivity - must be able to store > 100 kt/year CO_2 storage capacity seal integrity - capillary pressure/faulting tectonically stable area data availability implying confidence

Table 3: Qualitative weighting of site selection criteria and geological parameters.

Weighting	Explanation
+++	data from several boreholes, seismic data
++	some average values
+	some data estimated
-	many estimates
--	only few data
---	no data

Table 4: Industrial CO_2 sources in and around Szczecin, emission data from year 2004.

Company	Plant	Production	Emission [Mt]
Zaklady Chemiczne Police SA	Police EC (I&II)	chemical plant	0.629
POLCHAR Sp. z o.o.	Police	heating plant	0.188
Huta Szczecin SA	Szczecin	steel plant	0.267
Zespol Elektrowni Dolna Odra SA	Szczecin	power plant	0.276
Zespol Elektrowni Dolna Odra SA	Pomorzany	power plant	0.651
PEC Sp. z o.o.	Stargard Szczecinski	power plant	0.08
Zespol Elektrowni Dolna Odra SA	Gryfino	power plant	4.152
PCK Raffinerie GmbH Schwedt	Raffinerie Schwedt	refinery	4.07

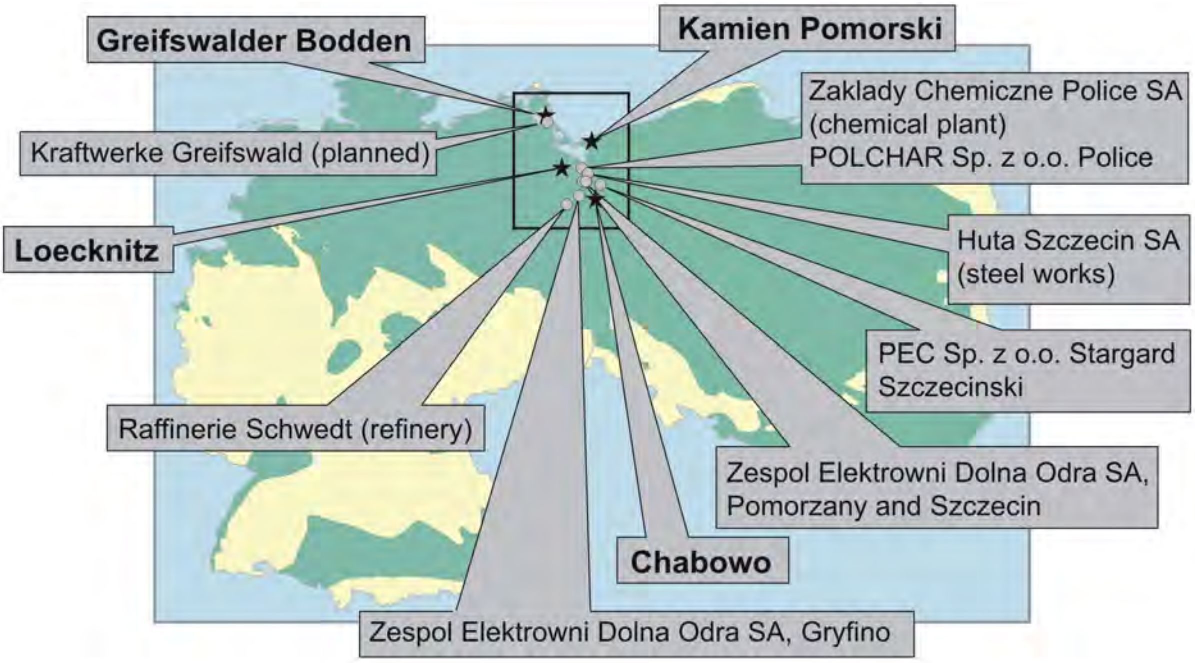

Figure 3: Industrial CO_2 sources and potential storage sites in the area of Szczecin in the Polish-German border region.

5.3 Application of the site selection criteria to the test case study

5.3.1 Basic site selection criteria

The parameter “sufficient depth for supercritical dense phase (> 800 m)” is fulfilled at all four sites. The source of information for this point is publicly available in structural maps. Usually, there are no data about injectivity (“sufficient injectivity to be economically viable”) of saline aquifers, unless detailed investigations have been performed, including modelling (Greifswalder Bodden). Of course, the injectivity of hydrocarbon fields is given by the production rate (Kamien Pomorski). Usually, the seal is scarcely described. Therefore the parameter “integrity of seal in terms of faults/capillary pressure” cannot be answered satisfactorily based on the information available for each of the case studies. For detailed information and weighting of parameters, see report D25 Application of standards.

5.3.2 Geological parameters

Data about the general description of storage sites like “trap type”, “storage type (e.g. hydrocarbon field/aquifer)”, “reservoir lithology type”, and “heterogeneity of system” are usually available. Data about the shape of sites like “areal extent”, “thickness of reservoir (min-max)”, “depth to crest (max-min)”, “depth to base of reservoir (max-min)” can be easily taken from structural maps. The petrographic parameters “porosity (max-min)”, “permeability (max-min)”, “pore volume”, “pressure”, “fracture pressure” and “temperature” can be found in a general quality in literature, data of better quality can be obtained from wells, if available. Data about seals like “seal lithology type”, “seal permeability”, “seal capillary pressure”, “seal pore entry pressure (can be estimated if permeability is known)”, and “faulting in seal” are usually missing but are in the same way and quality available as the petrographic parameters of the aquifers. Data about tectonic activity (“tectonically active”) are usually publicly available but not part of the existing reports on the current four storage sites. The “Availability of data” is about equal for the sites described in the framework of EU projects but much lower for the Loecknitz site. There is no information about “conflicts of interest”. For detailed information and weighting of parameters.

5.3.3 Ranking criteria

Since most often data about “depth” and “storage capacity” are available, these two ranking parameters are the most important ones. “Depth” is generally well known, whereas information on “storage capacity” is usually scarcer. For storage capacity estimation, a standard methodology procedure will be developed in GeoCapacity as part of WP4.2. “Injectivity - must be able to store > 100 kt/year CO_2” is also a useful parameter for HC fields and aquifer storage sites where some investigations have already been performed, but for many structures in saline aquifers there are no data available. This is also true for the parameter “seal integrity - capillary pressure/faulting”. The parameter “tectonically stable area” could be a useful ranking parameter like “depth”, but it has not been investigated. The last parameter, “data availability implying confidence” is a very subjective one and difficult to standardize. However, attempts have been made in this report using a weighting of parameters (Table 3 and Table 5).

5.3.4 Ranking of the four potential storage sites

Since costs in general will increase with increasing storage depth, the Chabowo site is the best option concerning “depth”. It is also the best option concerning “storage capacity”, followed by Greifswalder Bodden and, with a much smaller storage capacity, Loecknitz. Kamien Pomorski is actually the smallest site. As to “injectivity – must be able to store > 100 Mt/year CO_2”, a value exists from modelling of the Greifswalder Bodden site, but also Kamien Pomorski shows an acceptable injectivity by means of its production history. With regard to “seal integrity – capillary pressure/faulting” only scarce data exists for Chabowo and Kamien Pomorski, while there is no data for Loecknitz. Faults are present in Greifswalder Bodden, but no information about their sealing capacity exists. The criterium “tectonically stable area” is not applicable because of lack of information. The parameter “data availability implying confidence” is dealt with using a weighting of parameters after Table 3. For details of the ranking see Table 5. The result of the ranking of the four sites is that the best storage option is the Chabowo site followed closely by Greifswalder Bodden.

Table 5: Ranking the four potential storage sites.

Ranking criteria		**Chabowo**	**Greifswalder Bodden**	**Kamien Pomorski**	**Loecknitz**
Depth	value	840 m	1130 m	2232 m	
	data quality	+++	+++	+++	---
Storage capacity	value	500 Mt CO_2	443 Mt CO_2	3.36 Mt CO_2	>100 Mt CO_2
	data quality	+	+	++	+
Injectivity - must be able to store > 100 kt/year CO_2	value		40 kg/s (model)	oil production rate (~8-9 kg/s)	
	data quality	---	++	++	---
Seal integrity - capillary pressure/faulting	value	no faults	fault impermeability has to be checked	no faults	
	data quality	--	--	--	---
Tectonically stable area	value			yes	
	data quality	---	---	---	---
Data availability implying confidence		+	+	+	--
Rank		**1**	**2**	**3**	**4**

5.4 Conclusions

The basic site selection criteria cannot be fulfilled in any of the four sites because data are not publicly available. Geological parameters in a more general quality can be obtained very easily from maps or geological literature. More detailed information is available from well data or seismic data which often are the property of companies and therefore not available or only at high cost. Future desk studies of potential storage sites should include more information on the sealing formations and tectonic activity. Depth, tectonic activity, and storage capacity are useful ranking criteria because of data availability. The parameter “data availability implying confidence” should be standardized.

6 STORAGE CAPACITY STANDARDS

Storage capacity assessment begins with identifying sedimentary basins. The GeoCapacity project comprises most sedimentary basins suitable for geological storage of CO_2 located within the EU and the Central and Eastern European new member states and candidate countries. Figure 4 shows a European CO_2 storage prospectivity map with major CO_2 emission point sources. This is not a map of actual storage capacity, but a map of where to look for storage capacity.

Once the suitable sedimentary basins in a region or country have been outlined the next step is to identify potential reservoir and sealing units for CO_2 storage and characterization of their geological and physical properties. At this point regional CO_2 storage estimates based on the bulk volume of aquifers can be calculated. More precise estimates can be provided if stratigraphic or structural traps with suitable reservoir and sealing properties are identified within the aquifers and the storage potential of the individual trap is calculated. Regional estimates can now be calculated as the sum of storage potential of all the traps identified.

Previous assessments of geological storage capacity of different countries, areas and regions show large variations in the quality and detail of the work. In GeoCapacity we have been aiming at adapting and defining common standards in order to produce uniform assessments of geological storage capacity.

The work with establishing internationally recognised standards for capacity assessments was initiated by the Carbon Sequestration Leadership Forum (CSLF) about a year before the start of the GeoCapacity project and a CSLF Task Force has been active since. The paper “Estimation of CO_2 Storage Capacity in Geological Media - Phase 2“ (Bachu et al., 2007) published by the CSLF presents comprehensive definitions, concepts and methodologies to be used in estimating CO_2 storage capacity. The GeoCapacity project has contributed to this work with several project participants being members of the Task Force and co-authors on the paper. Simultaneously the GeoCapacity project has continued the progress on these issues also in Europe.

The CSLF paper on capacity standards forms the basis for the work with capacity estimations in GeoCapacity and the goal of this deliverable report is to review the GeoCapacity applications of the methodologies described in the paper. In the following the methodologies used in GeoCapacity for CO_2 storage capacity estimations in deep saline aquifers, hydrocarbon fields and coal beds, respectively, will thus be described.

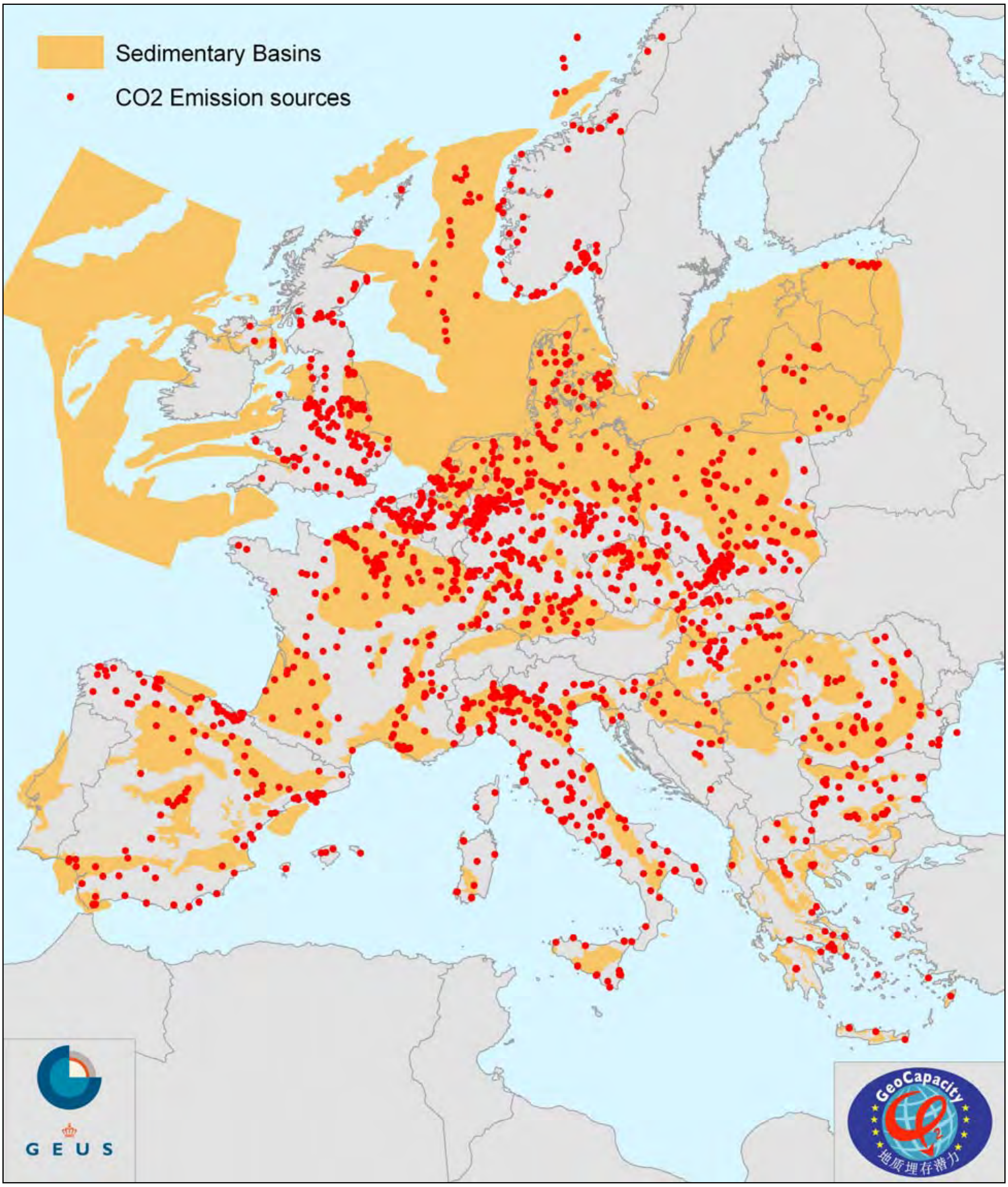

Figure 4: European CO_2 storage prospectivity map with major CO_2 emission point sources.

6.1 The resource-reserve pyramid concept

In GeoCapacity we have chosen to use a simplified version of the resource-reserve pyramid presented in Bachu et al. (2007), where we do not distinguish between practical and matched storage capacity in the upper part of the pyramid (Figure 5). Both practical and matched storage capacity estimation is more detailed than most of the regional work required in GeoCapacity for populating the database with potential storage. However some of the case studies carried out in WP 2 may qualify to be placed in the top of the pyramid.

The storage capacity estimates provided in the GeoCapacity database are generally regional estimates based on the bulk volume of a deep saline aquifer or site specific estimates; in both cases including a storage efficiency factor in the calculation, i.e. being effective storage capacity estimates belonging in the middle of the pyramid. Theoretical storage capacities without any storage efficiency factor applied are unrealistic, not useful and lead only to misunderstanding and in GeoCapacity we suggest not to use theoretical capacities.

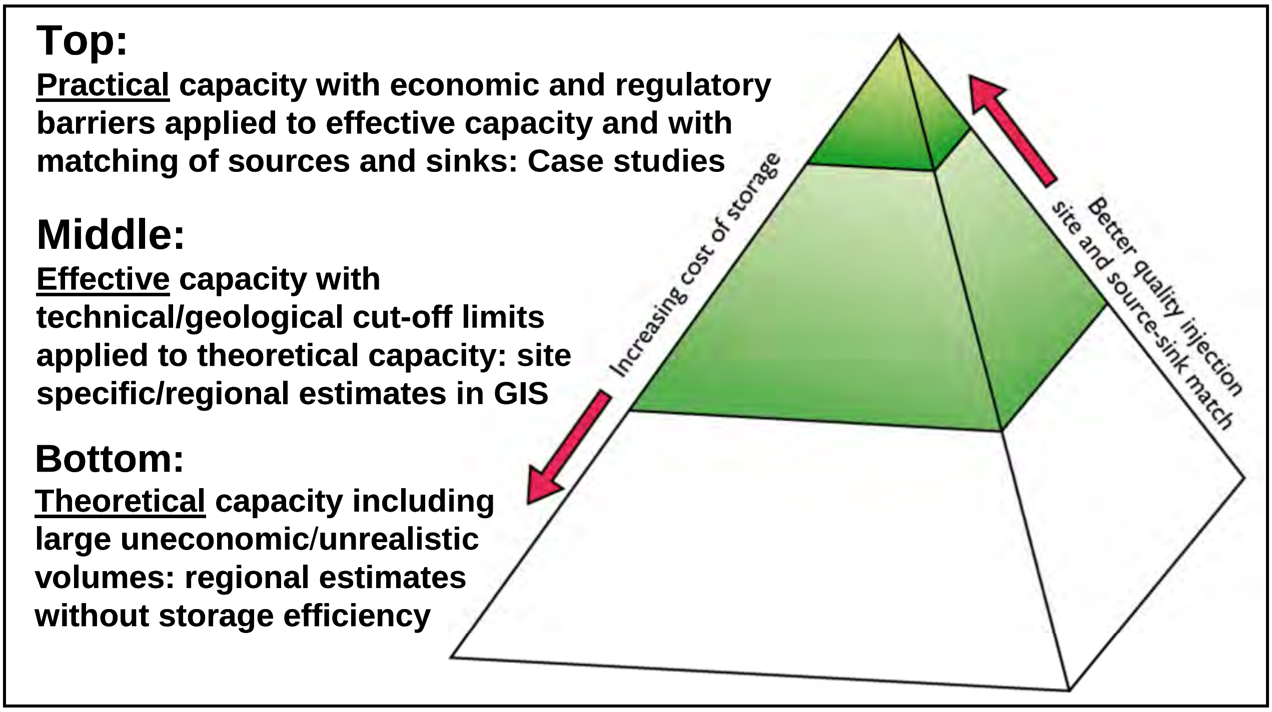

Figure 5: Resource-reserve pyramid concept adopted in GeoCapacity. Notice that the lower part of the pyramid, representing the theoretical storage capacity is left blank as we suggest not using this unrealistic approach to storage capacity.

7 CAPACITY ESTIMATION IN DEEP SALINE AQUIFERS

The approach used in GeoCapacity for storage capacity estimation in deep saline aquifers is slightly simplified and/or modified versions of the formulas presented in Bachu et al. (2007). In their paper both theoretical and effective storage capacity for a basin or region are defined as the sum of the storage capacity of individual structural or stratigraphic traps in the said area/volume. The authors then distinguish between theoretical and effective storage capacity by applying a storage efficiency factor (capacity coefficient). The efficiency factor includes the cumulative effects of trap heterogeneity, CO_2 buoyancy and sweep efficiency, but no values or range of values are given as the factor is site-specific and needs to be determined through numerical simulations and/or field work.

Detailed site evaluation in terms of numerical simulation and field work etc. goes beyond the scope of work for a regional storage capacity assessment project like GeoCapacity. Therefore the emphasis in GeoCapacity has been to define a pragmatic approach for the storage efficiency factor as theoretical storage capacity is not regarded useful. We define the storage efficiency factor as the ratio of used space over available space either considering a trap structure or a regional aquifer and we would like to introduce effective regional storage capacity estimates based on bulk volume of aquifers and applying a storage efficiency factor as a supplement to regional estimates based on the sum of capacity in individual identified traps.

Thus the formula for storage capacity estimation is the same for aquifer traps and regional aquifers:

$$M_{CO2} = A \times h \times NG \times \phi \times \rho_{CO2r} \times S_{eff}$$

where:

M_{CO2}: regional bulk or trap specific storage capacity
A: area of regional or trap aquifer
h: average height of regional or trap aquifer
NG: average net to gross ratio of regional or trap aquifer (if unknown, use suggested default)
ϕ: average reservoir porosity of regional or trap aquifer (best estimate)
ρ_{CO2r}: CO_2 density at reservoir conditions (if unknown, use suggested default)
S_{eff} : storage efficiency factor (for bulk volume of regional aquifer or trap specific)

7.1 Regional estimates based on bulk volume of aquifers

As an early stage assessment, regional estimates building on basic and non-detailed geological information can be informative and helpful. Therefore we propose a calculation formula for regional estimates that are based on bulk volume of the aquifer and not on trap volumes and thus not include an evaluation of the presence and extent of structural and stratigraphic traps. The storage efficiency factor in the context of Bachu et al. (2007), is trap/site specific and not applicable to the bulk volume of a regional aquifer. An estimate based on the bulk volume of a regional aquifer is therefore by nature theoretical. On the other hand theoretical storage capacity estimates are not very useful as they include unrealistic and uneconomic volumes based on assumptions that we know for sure are not valid.

In GeoCapacity we therefore suggest to use a storage efficiency factor of 2 % for bulk volumes of regional aquifers, based on work by the US DOE. In Frailey (2007), Monte Carlo simulations result in a P50 between 1.8 and 2.2 % for the storage efficiency factor of the bulk volume of a regional aquifer (with low and high values of 1 % and 4 %, respectively). The work includes Monte Carlo simulations of the distribution of values for a number of terms defining the pore volumes for a regional aquifer and a number of terms reflecting local formation effects in the injection area of a specific well.

In Bachu et al. (2007) they include the net to gross ratio (NG) in both the theoretical and the effective capacity estimate which is meaningful when assessing individual traps. The net to gross ratio is, however, also a site specific parameter depending very much on the local geological variations and is not necessarily either well known or equally distributed throughout a region. It may therefore not be meaningful to establish an average value for a regional aquifer based on very few observations. If limited information is available we suggest that a default value of 0.25 is used. This value may be too high in some cases, but will in many cases be a conservative value.

When taking the NG ratio into consideration it should normally be possible to provide a best estimate of the reservoir porosity of a regional aquifer.

The CO_2 density is a function of pressure and temperature and can be obtained from different models, e.g. described in Span and Wagner (1996) or Peneloux et al. (1982). As for NG it may not be meaningful to establish an average value for a regional aquifer based on very few observations. If limited information is available we suggest that a default value of 0.650 t/m^3 is used.

As a regional estimate is based on the bulk volume of an aquifer and not on trap volumes it is already subject to great uncertainty (thickness and extent of aquifer, storage efficiency factor etc.) the exact values of the net to gross ratio and the CO_2 density are not essential. Furthermore, as the value of the storage efficiency factor is generalized rather than based on specific geological conditions a regional estimate calculated using this methodology should be regarded as only indicative.

7.2 Regional estimate based on trap volumes

If the knowledge and level of detail exists and are available the optimal way of performing regional capacity estimates is of course to provide estimates of effective storage capacity of individual traps. Such estimates are typically based on trap volumes and known values (usually from wells) for the net to gross ratio, porosity, CO_2-density and storage efficiency factor. The regional estimate will then be the sum of the storage capacity of all the identified traps. The proposed formula to be applied on the individual traps is the same as for regional estimates, but the conditions for the parameters are different, especially in the case of the storage efficiency factor as described in the following sections.

As previously described the capacity estimation standards in the GeoCapacity project is based on the work and publications by the CSLF, Bachu et al. (2007). However, no advice is given by the CSLF on values for the trap specific storage efficiency factor other than it will be very site-specific. The discussions on storage efficiency factor in several research projects, have though led to the initiation of further work on this issue by the IEA and the CSLF, proving the synergetic effects between projects.

In the following, two different approaches used in GeoCapacity for the trap specific storage efficiency factor will be described. One for open or semi-closed aquifer systems, the "cartoon approach" and one for closed aquifer systems, the "table approach".

7.2.1 Trap specific storage efficiency factor for open and semi-closed aquifer systems

Figure 6 shows a conceptual model for a trap structure in an unconfined aquifer. Storage of CO_2 only takes place within the trap, but storage space is generated by displacing existing fluids and distributing pressure increase in the surrounding and connected aquifer system. The available space is thus the pore volume within the trap and the storage efficiency factor is the used fraction of the available space and depends on the connectivity to the surrounding aquifer.

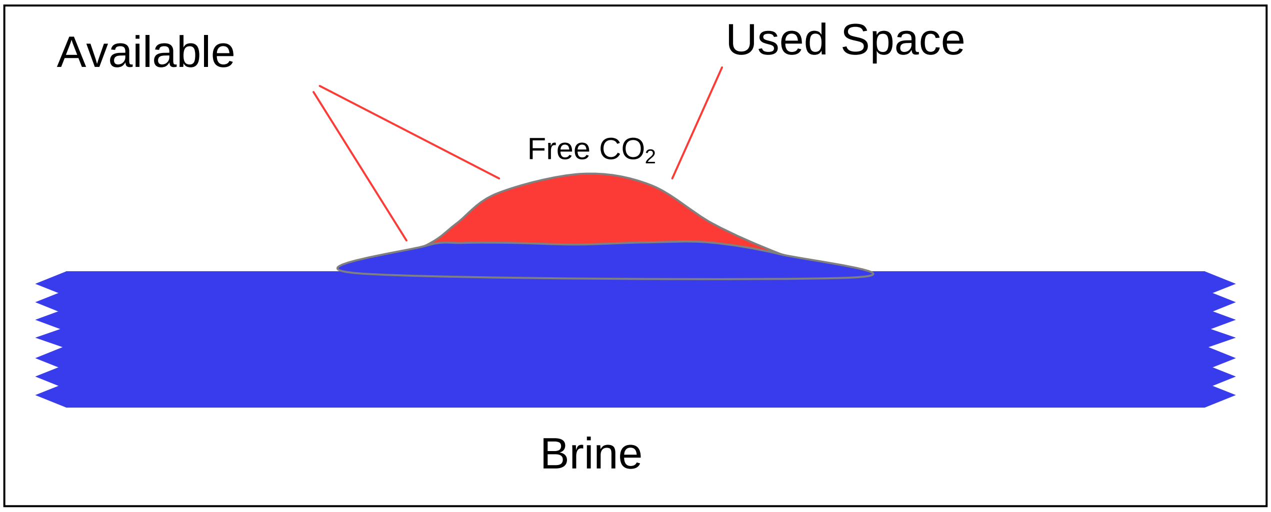

Figure 6: Conceptual model for a trap structure in an unconfined aquifer.

The "cartoon approach", depicted in Figure 7: Illustration of the "cartoon approach" for storage efficiency factor. Figure 7, assumes such a trap in an open (unconfined) or semi-closed aquifer and distinguishes between high and low quality reservoirs. A high quality reservoir is determined as a reservoir with good porosity and permeability conditions and e.g. a low degree if compartmentalisation and opposite for a low quality reservoir. If there are no structural or stratigraphic limitations in the connectivity between the trapped aquifer volume and the bulk aquifer volume (situation 1 in Figure 7) a storage efficiency factor of 40 % and 20 % is assumed for high and low quality reservoirs, respectively. In situations 2-4 the red lines indicate bounding faults, but could symbolise any feature limiting the connectivity between the trapped aquifer volume and the bulk aquifer volume and the storage efficiency factor is assumed to decrease correspondingly with decreasing connectivity.

The upper estimate of 40 % storage efficiency factor is based on experience from natural gas storage facilities in France, Germany and Denmark and is supported by a numerical simulation of CO_2 injection in Bunter Sandstone reservoirs in the UK sector of the southern North Sea in Brook et al. (2003) and of the numerical simulation of CO_2 injection in the Havnsø Structure onshore Denmark in Bech and Larsen (2005). The principle of the approach is simple and the suggested decrease in storage efficiency factor with decreasing reservoir quality and decreasing connectivity to surrounding aquifer is very tentative. Hence the "cartoon approach" should be used only as a rule of thumb in connection with regional estimates and not for detailed site specific estimates of storage capacity.

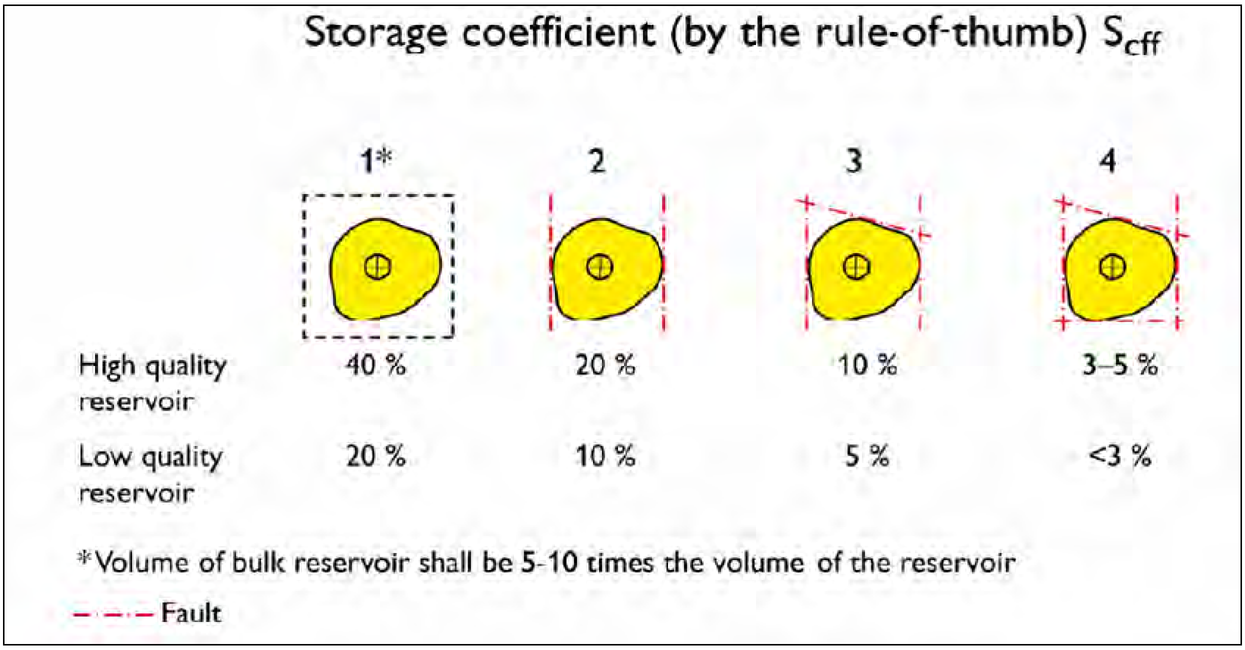

Figure 7: Illustration of the "cartoon approach" for storage efficiency factor.

7.2.2 Trap specific storage efficiency factor for closed aquifer systems

Figure 8 shows a conceptual model for a trap structure in a closed aquifer. Storage of CO_2 only takes place within the trap, but existing fluids cannot be displaced outside the aquifer system. Hence, storage space is only generated through pressure increase and compressibility in the affected space. Like for the open aquifer system the available space is the pore volume within the trap and the storage efficiency factor is the fraction of the available space used, but now it depends on the allowable average pressure increase, the compressibility and the ratio of trap volume to affected volume as shown below.

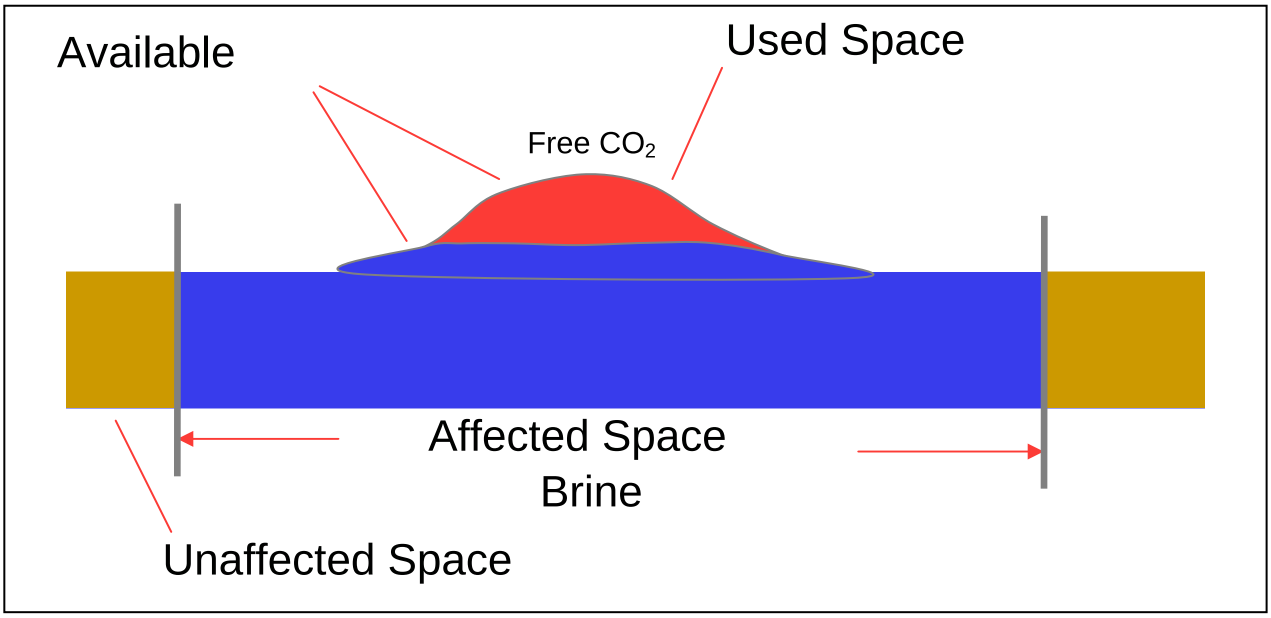

Figure 8: Conceptual model for a trap structure in a closed aquifer.

The volume of CO_2 (V_{CO2}) that can be stored in a closed system depending on the entire available pore volume ($\varphi \times NG \times V_{bulk}$) in the affected space (bulk volume), the total compressibility (c) and the allowable average pressure increase (Δp) and is given by:

$$V_{CO2} = c \times \Delta p \times \varphi \times NG \times V_{bulk}$$

We define the total compressibility (c) as:

$$c = c_{pore} + c_{fluid}$$

Storage space in a closed system is created by increased pore space and increased fluid density (compression of the fluid), both due to pressure increase induced by the CO_2 injection. Storage space created by compression of the matrix is negligible. Hence the pore compressibility (c_{pore}) is reflecting change of porosity with change of pressure and the fluid compressibility (c_{fluid}) is reflecting change in fluid density with change of pressure. With:

$$S_{eff} = V_{CO2} / (\varphi \times NG \times V_{trap})$$

This gives us:

$$S_{eff} = V_{CO2} /(\varphi \times NG \times V_{trap}) = (c \times \Delta p \times \varphi \times NG \times V_{bulk})/(\varphi \times NG \times V_{trap}) = c \times \Delta p \times (V_{bulk} / V_{trap})$$

Table 6 shows the trap storage efficiency factor, for a closed aquifer at a depth between 1000 m and 3500 m, and for a total aquifer affected volume that is up to 100 times the volume of the trap structure. It is further assumed that the allowed average pressure increase in the affected space is 10 % of the hydrostatic pressure and that c is 10^{-4} bar^{-1} ($c_{pore} \approx 6 \times 10^{-5}$ and $c_{fluid} \approx 4 \times 10^{-5}$). We call this the “table approach”. The assumptions used in the “table approach” has the effect that more CO_2 can be stored in deeper aquifers, other parameters equal, due to higher allowable pressure increase with depth.

Table 6: Trap storage efficiency factor (in percent), the “table approach”.

	V_{bulk} / V_{trap}				
Depth (m)	**1**	**5**	**10**	**50**	**100**
1000	0.10	0.5	1.0	5	10
1500	0.15	0.8	1.5	8	15
2000	0.20	1.0	2.0	10	20
2500	0.25	1.3	2.5	13	25
3000	0.30	1.5	3.0	15	30
3500	0.36	1.8	3.6	18	36

The first column in Table 6 gives the trap storage efficiency for a trap that is not connected to an aquifer volume outside of the trap. As a result, the storage efficiency is quite low, as space for CO_2 inside the trap can only be created by pressure increase in the trap volume. If pressure increase can be accommodated by the aquifer volume outside the trap, the trap storage efficiency factor can increase to values as high as 30 – 40% for large aquifers. Whether the values given in the table are realistic for a specific storage site depends on such factors as the injection strategy, the trap structure and the dynamic behavior of CO_2 during the injection phase. A detailed geological model must be constructed to model the migration of CO_2 through the aquifer and the accumulation in the trap structure. Values such as those given in Table 6 can only serve as an indication of the storage potential.

7.2.3 Conclusive remarks on trap specific storage efficiency factor

In GeoCapacity we have suggested different approaches for individual structural or stratigraphic traps. The most simple is the “cartoon approach”, assuming that the surrounding aquifer is an open or semi-closed system and suggesting rule-of-thumb storage efficiency values in the range between 3 % and 40 % for semi-closed low quality and open high quality reservoirs, respectively.

The “table approach” is assuming closed aquifer systems and is based on trap to aquifer volume ratio, total compressibility and allowable average pressure increase. This approach suggests a range of storage efficiency factors depending on depth (i.e. pressure) and trap to aquifer volume ratio. For a reservoir at a depth of 2000 m, the respective storage efficiency factor for trap to aquifer volume ratios of 5, 10, 50 and 100 is 1 %, 2 %, 10 % and 20 % assuming a maximum allowable average pressure increase of 10 % of the hydrostatic pressure and a total compressibility (pore + fluid) of 10^{-4} bar^{-1}.

An allowable pressure increase of 10 % may be a conservative assumption and in Zhou et al. (2008) they use a sustainable pressure buildup for a formation-seal system of 50 % of the initial hydrostatic pressure. Furthermore their results indicate, that seals may be considerably less impermeable to brine than to CO_2 because of combined capillary and permeability barriers. Such leaking of native brine through non-ideal seals (on top, adjacent to or below the storage formation) will help to reduce the pressure buildup and may cause closed systems to act more like semi-closed or semi-closed more like open systems.

In summary the following guidelines are recommended for capacity estimation in deep saline aquifers:

- Theoretical storage capacity is unrealistic and should never be considered definitive
- It is necessary to distinguish between estimates for regional aquifers and estimates for individual structural or stratigraphic traps
- The choice of storage efficiency factor for traps is partly dependent on whether the aquifer system is open, semi-closed or closed
- The choice of storage efficiency factor for traps can be based on either a rule-of-thumb approach for open and semi-closed aquifer systems or trap to aquifer volume ratios and allowable pressure increases for closed aquifer systems
- Storage capacity estimates should always be accompanied with information on assumptions and the approach for storage efficiency factor

The m*aximum storage capacity* of a closed aquifer system is simply the total space created by a pressure increase and the subsequent compressibility of all the substances in the affected space. The affected space is the entire volume of the subsurface that during the storage time has its state or qualities changed by the storage operation. The storage capacity is proportional to the pressure increase, compressibility, affected volume and total projected injection volume. Once the difficulty of data selection has been overcome, the calculation of this capacity is fairly straightforward. For a given subsurface space we can calculate the maximum volume of CO_2 that can be stored – or, if we have a given volume of CO_2 to store, we can calculate the minimum subsurface volume (affected space) needed.

The *injectivity* and the formation pressure conductivity could play an important role in the storage capacity of a geological formation. The number of wells, well spacing and well stimulation actions can be important in an operational or economic sense, but have little influence. In GeoCapacity deliverable D24 Storage capacity standards (Vangkilde-Pedersen et al., 2008) a simple method is presented that estimates the pressure within the injection location for a given permeability and given injection rate. It is shown that the maximum injection rate at a permissible maximum pressure could restrict the instant storage capacity of a CO_2 storage site. This restriction becomes more significant with lower (average) permeability.

8 CAPACITY ESTIMATION IN HYDROCARBON FIELDS

The methodology used for storage capacity estimates for hydrocarbon fields in the GeoCapacity database are described in section 8.1 and in section 8.2 a model for more precise and detailed capacity estimates in oil fields including EOR is described

8.1 Methodology used for estimates in database

For calculation of CO_2 storage capacity in hydrocarbon fields we also use the methodology described in the CSLF paper Bachu et al. (2007) using the formulas:

$$M_{CO2} = \rho_{CO2r} \times R_f \times (1-F_{ig}) \times OGIP \times B_g$$

and

$$M_{CO2} = \rho_{CO2r} \times (R_f \times OOIP \times B_o - V_{iw} + V_{pw})$$

For gas and oil fields respectively and where:

M_{CO2}: hydrocarbon field storage capacity
ρ_{CO2r}: CO_2 density at reservoir conditions (best estimate)
R_f: recovery factor
F_{ig}: fraction of injected gas
OGIP: original gas in place (at surface conditions)
B_g: gas formation volume factor << 1
OOIP: original oil in place (at surface conditions)
B_o: oil formation volume factor > 1
V_{iw}: volume of injected water
V_{pw}: volume of produced water

For a number of countries a simplified formula from the GESTCO project has been used (Schuppers et al., 2003):

$$M_{CO2} = \rho_{CO2r} \times UR_p \times B$$

where:

M_{CO2}: hydrocarbon field storage capacity
ρ_{CO2r}: CO_2 density at reservoir conditions (best estimate)
UR_p: proven ultimate recoverable oil or gas
B: oil or gas formation volume factor

Here UR_p in fact represents $R_f \times$ OGIP and $R_f \times$ OOIP, respectively, but the formula does not take F_{ig}, V_{iw} and V_{pw} into account. UR_p is the sum of the cumulative production and the proven reserves and typically the methodology for calculating/estimating the proven reserves vary from country to country.

Each country has provided the expected ultimate recoverable oil or gas from their hydrocarbon fields for the GeoCapacity database. Typically based on the sum of produced volumes and expected reserves and given field by field. In some countries only the sum for the entire sector is available and in such cases methods taking into account e.g. the area of individual fields has been used. For each country a minimum and maximum ultimate recoverable oil and gas has been calculated, typically by multiplying the expected ultimate recoverable oil and gas with a fixed conversion factor based on the local/regional experience.

Finally, for each country a proven ultimate recoverable oil and gas has been calculated, typically using a fixed conversion factor applied to the expected ultimately recoverable oil and gas. For some countries, however, proven ultimate recoverable oil and gas is given as the sum of produced volumes and the lowest estimate for reserves for each field.

The formation volume factor used for oil varies regionally and/or locally depending on the oil type and the formation volume factor used for gas varies with depth as a function of pressure and temperature. Also the CO_2 density varies with depth as a function of pressure and temperature. Both may, however, in some countries have been applied as constant average values to all hydrocarbon fields.

The methodology used for hydrocarbon fields yield theoretical storage capacity according to the methodology described by the CSLF. To reach effective storage capacity the CSLF introduce a number of capacity coefficients representing mobility, buoyancy, heterogeneity, water saturation and aquifer strength, respectively, all of which reduce the storage capacity. However, there are very few studies and methodologies for estimating the values of these capacity coefficients and hence we have chosen in GeoCapacity not to distinguish between theoretical and effective storage capacity for hydrocarbon fields.

8.2 Model for storage capacity estimation and EOR in oil fields

Within work package 3 of the GeoCapacity project, a model for estimation of CO_2 storage capacities of oil reservoirs incorporating the production of additional oil associated with the CO_2 storage process (Bossie-Codreanu, 2008) has been developed. The model assumes miscible CO_2 flooding (secondary or tertiary) prior to CO_2 storage without oil production. The model is based on the following steps:

1) Miscibility Test
The model determines whether miscibility develops:
- At the beginning of the CO_2 storage
- At the end of the CO_2 storage: this pressure is usually the initial reservoir pressure at discovery

2) Oil recovery and CO_2 storage calculation under miscible conditions
This step calculates oil recovery and CO_2 storage in two stages:
- Until the breakthrough of the CO_2
- After the breakthrough of the CO_2, assuming that CO_2 is recycled

3) CO_2 storage without oil production
This step accounts for the amount of CO_2 to be stored under a given pressure difference between the initial injection pressure and the final pressure, often chosen as the initial reservoir pressure at discovery.

This model, especially concerning Step 2, follows the Shaw and Bachu model (Shaw and Bachu, 2002). The only difference is that the percentage of CO_2 trapped during the oil recovery step after breakthrough of CO_2 is set to 50% whereas Shaw and Bachu considered that 60% may be trapped. Thus, our model will result in more pessimistic storage estimations.

This overall approach should be considered as an effort to estimate the co-optimization of CO_2 storage and as such should be considered as an intermediate model between a single formula and complex modelling such as a numerical model. Single formula expressions either set a given storage factor (e.g. 6% for aquifers) or in oil fields considers the replacement of oil produced by the injected CO_2 without any consideration for the additional oil which could be produced by EOR. Such formulas may oversimplify the CO_2 problem, but on the other hand, numerical modeling requires a rich database, making the study too long for quick estimations. This model is a rapid estimator of the oil recovery and the CO_2 storage capacity and can lead to quick parametric studies. Table 7 below shows a list of the data required for the model.

Table 7: List of data needed for the model.

Initial Pressure	From data Base or Depth vs. P gradient
Initial Temperature	From Data Base or Depth vs. T gradient
API	From Data Base
Original Oil in Place	From Data Base
Production	From Data Base
Oil Density	From Data Base
CO_2 Viscosity	From correlation (Fenghour, Wakeham & Vesovic, 1998)
Oil Viscosity	From Data Base
P when CO_2 inj. starts	From Data Base – user defined – adjusted eventually for the MMP
C Term	2.52 for 5-spots and 2.12 for line drive
CO_2 Density	From EOS (Span and Wagner)
Q – CO_2 injection	User defined – used in the gravity term
Area	From Data Base
Horizontal Kh	From Data Base
Vertical Kv	From Data Base or 1/10 Kh
Res. Thickness	From Data Base
Heterogeneity Index, VDP VDP=0 – homogeneous VDP=1 - heterogeneous	From Kmin and Kmax – determination of the index which generates a log-normal distribution from Kmin to Kmax
Irreducible Water Saturation	From Data Base
Water Salinity	From Data Base
Porosity	From Database or calculated
Associated Gas Gravity	From Data Base or calculated from composition
Sorg	User defined
Sorw	User defined
WOR	From Data Base or calculated from production
Bg	Calculated
Z-co_2	From EOS

9 CAPACITY ESTIMATION IN COAL BEDS

The methodology for assessment of CO_2 storage capacity in unmineable coal beds (with methane content) is generally based on an estimation of either GIP (original gas in place) or PGIP (producible gas in place – from the viewpoint of Enhanced Coal Bed Methane [ECBM] technology). Depending on what level of the reserve-resource pyramid we are referring to, more or less detailed information on methane content (basin wide or for particular field) is taken into account.

In general, the approach and methodology already applied in GESTCO for the assessment of CO_2 enhanced coal bed methane recovery (CO_2-ECBMR) potential of un-mined coal fields were also employed in GeoCapacity. The work is based on the use of GESTCO reports on CO_2-ECBMR potential for Belgium (van Tongeren & Laenen, 2001), Germany (May, 2003) and Netherlands (van Bergen & Wildenborg, 2002).

Two quantities are important for calculating CO_2-ECBMR potential – producible gas in place (PGIP) and CO_2 storage capacity, which is a function of PGIP, CO_2 (gas) density and CO_2 to CH_4 exchange ratio (ER). PGIP means coal bed methane reserves for CO_2-ECBMR economic use (it differs from regular estimations of CBM reserves assuming the use of standard production measures). CO_2 storage capacity *S* denotes quantity of CO_2 which could replace PGIP, to the extent specified by ER (hard/bituminous coal has usually the ratio of about 2, brown coal and lignite may have higher ratios):

$$S = PGIP \times CO_2 density \times ER$$

where

PGIP = (Pure*) Coal Volume × Coal density × CH_4 content × Completion factor × Recovery factor;
(*excluding ash and moisture, if CH_4 content refers to pure coal samples).

The standard approach for calculating *PGIP* include estimation of volume and mass of (pure) coal within the seam(s), based on geological maps (structure maps and thickness maps) and coal density assessment from laboratory measurements and well logging information. The methane content in the coal is typically based on qualified estimates from laboratory measurements of drill core samples while recovery factor and completion factor is typically based on qualified guessing (recovery factor typically ranges from 0.2-0.85, after Bergen & Wildenborg (2002); completion factor might be 0.7, after RECOPOL).

In a number of GeoCapacity countries, preliminary estimations of CO_2 storage capacities in un-mined coal fields were already carried out either in CASTOR WP1.2 or in national projects. These calculations have been revised in GeoCapacity and where sufficient and reliable data were available they have been supplemented and unified according to principles applied already in the GESTCO project.

The coal field storage capacities provided in the GeoCapacity database can generally be placed in the middle part of the recourse-reserve pyramid, but closer to the base than to the top. Below is an example showing where different types of storage estimates for coal fields belong using an example from Poland:

- In the bottom of the pyramid is theoretical capacity estimated using *GIP* (gas in place, recourse and not reserve) instead of *PGIP*: *GIP = (Pure*) Coal Volume* x *Coal density* x *CH_4 content; S = GIP x CO_2density x ER*. This estimation is usually calculated for coal basin areas or bigger fields.
- In the lower middle part of the pyramid is semi-effective capacity estimated for entire coal basins based on PGIP and averaged values of coal bed parameters for the whole basin.
- In the upper middle part of the pyramid is (almost) effective capacity of individual coal/CBM fields and calculated as described in the beginning of this section with more site specific information/assumptions. If we use a reservoir simulator like CoalSeq and have sufficient and reliable input, we can provide better estimates of the recovery factor for the cases that we simulate. For example in case of the RECOPOL site, methane production with the use of CO_2-ECBMR is about 70 % higher than without CO_2-ECBM. This might suggest that a recovery factor of about 0.35 is realistic for bituminous coal of low permeability (quite common in a number of European countries – EU GeoCapacity partners), which is slightly lower than usual assumuptions. So, in such a case we would have a reliable estimation of Effective Capacity.

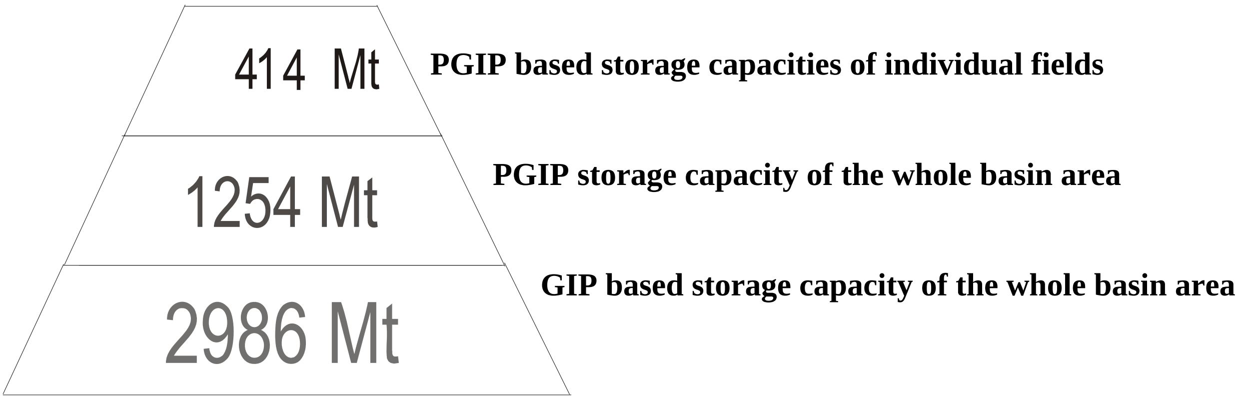

Figure 9: Example of resource-reserve pyramid for Polish Silesian Coal Basin (D10)

10 APPLICATION OF ESTIMATION STANDARDS TO TEST AREA

This section comprises application of the capacity estimation standards to a test area and sensitivity analysis of change in storage capacity based on different methodology. The chosen test area is the Danish sedimentary basin.

10.1 The Danish sedimentary basin

The geology of the major part of the Danish area is dominated by a large sedimentary basin, the Danish Basin, bounded to the north-east by the Fennoscandian Border Zone. The southern part of the Danish area is influenced by another large basin, the North German Basin and the two basins are separated by the Ringkøbing-Fyn High (Figure 10).

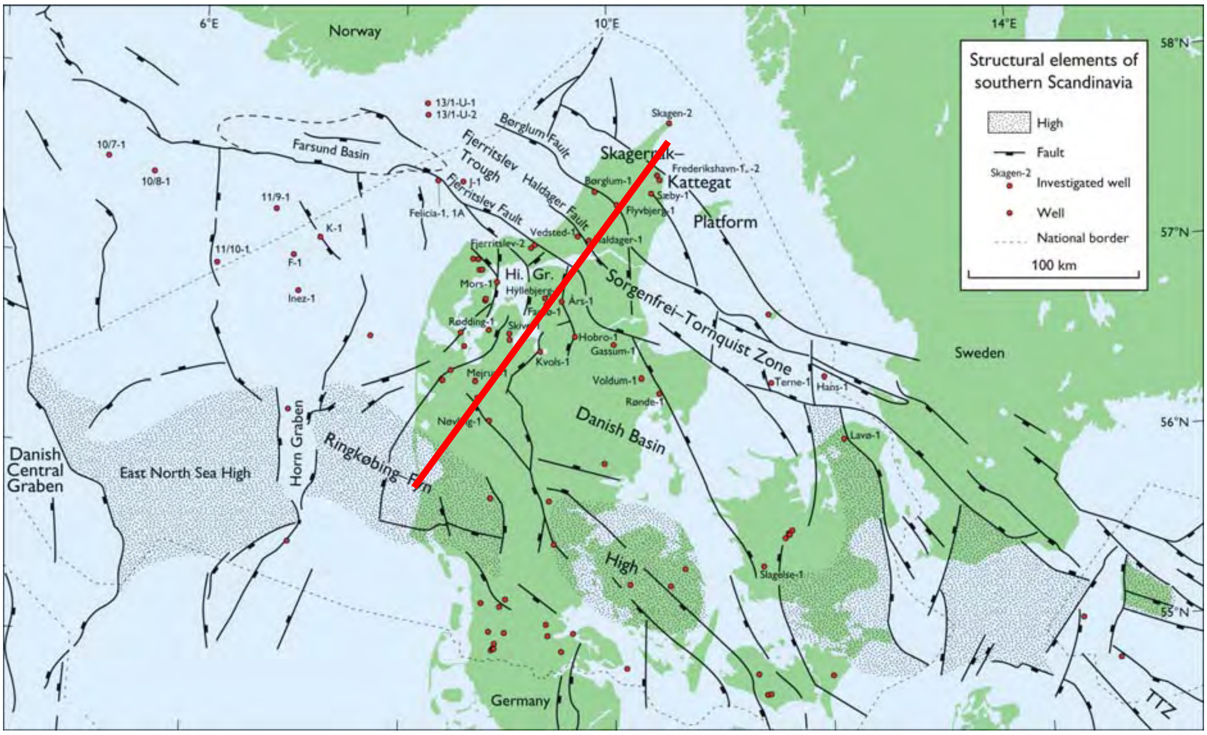

Figure 10: The principal structural elements of southern Scandinavian including the Danish Basin, the Sorgenfrei-Tornquist Zone, Skagerrak-Kattegat Platform and the Ringkøbing-Fyn High. Position of geological cross-section shown in Figure 11 is indicated by a red line.

The Danish Basin is characterised by an up to 9 km thick succession of sedimentary rocks of Late Palaeozoic to Cenozoic age (Figure 11). The sedimentary succession is affected by mainly northwest–southeast striking normal faults. Locally, over salt structures for instance, the succession is deeply truncated. The geology of the test area is described in more detail in the GeoCapacity deliverables D11/D12 and D17.

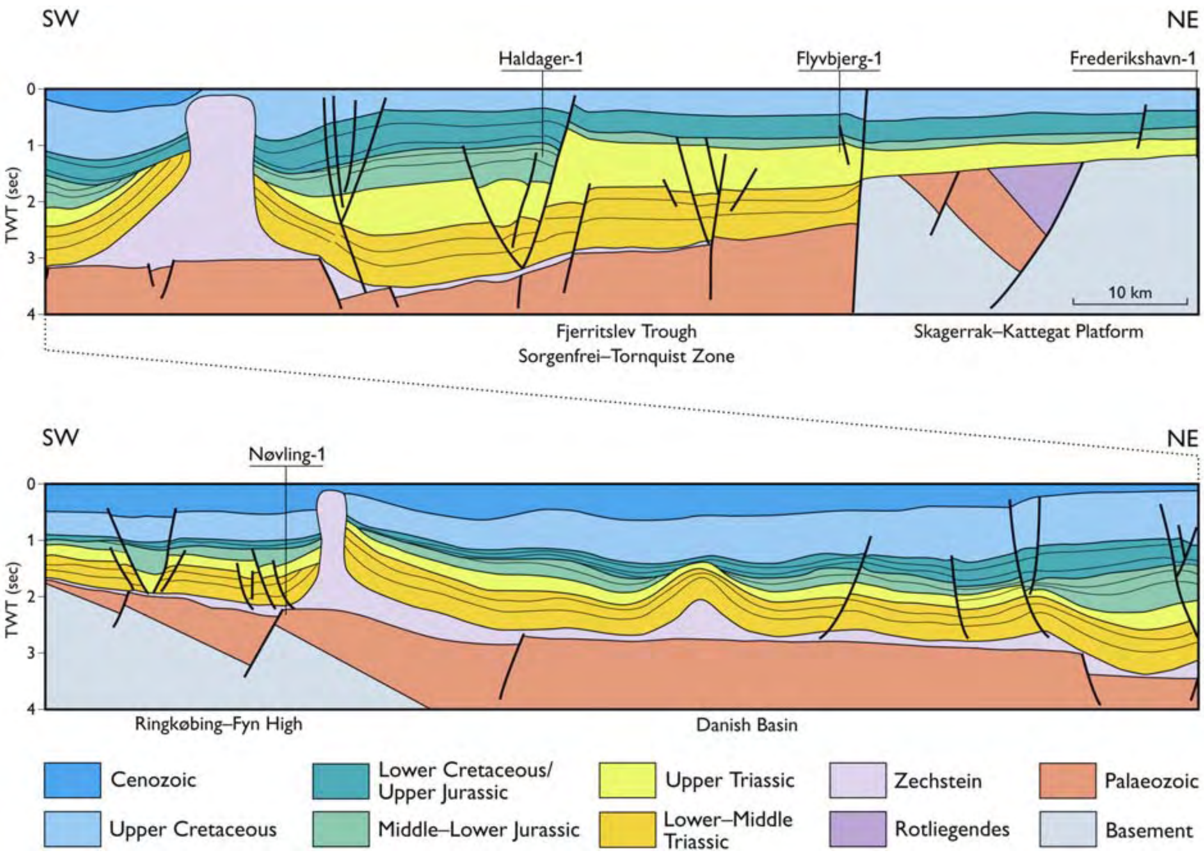

Figure 11: Geological cross-section trending SW–NE across the Danish area from the Ringkøbing-Fyn High (SW) to the Skagerrak-Kattegat Platform (NE).

10.2 Deep saline aquifers

In Bachu et al. (2007) both theoretical and effective storage capacity for a basin or region are defined as the sum of the storage capacity of individual structural or stratigraphic traps in the said area/volume. The authors then distinguish between theoretical and effective storage capacity by applying a storage efficiency factor (capacity coefficient) to the calculation. The efficiency factor includes the cumulative effects of trap heterogeneity, CO_2 buoyancy and sweep efficiency, but no values or range of values are given as the factor is site-specific and needs to be determined through numerical simulations and/or field work.

Detailed site evaluation in terms of numerical simulation and field work etc. goes beyond the scope of work for a regional storage capacity assessment project like GeoCapacity. Therefore the emphasis in GeoCapacity has been to define a pragmatic approach for the storage efficiency factor as theoretical storage capacity is not regarded as useful. We define the storage efficiency factor as the ratio of used space over available space either considering a trap structure or a regional aquifer and we also include effective storage capacity estimates based on the bulk volume of regional aquifers and applying a storage efficiency factor.

10.2.1 Regional estimates based on bulk volume of aquifers

Figure 12 shows simplified stratigraphy and lithostratigraphy of the sedimentary succession in the Danish Basin. Four regional aquifer systems have been identified, the Bunter Sandstone and

Skagerrak Formations, the Gassum Formation, the Haldager Formation and the Frederikshavn Formation. In Figure 13 the areal extent and thickness of the aquifer systems are shown.

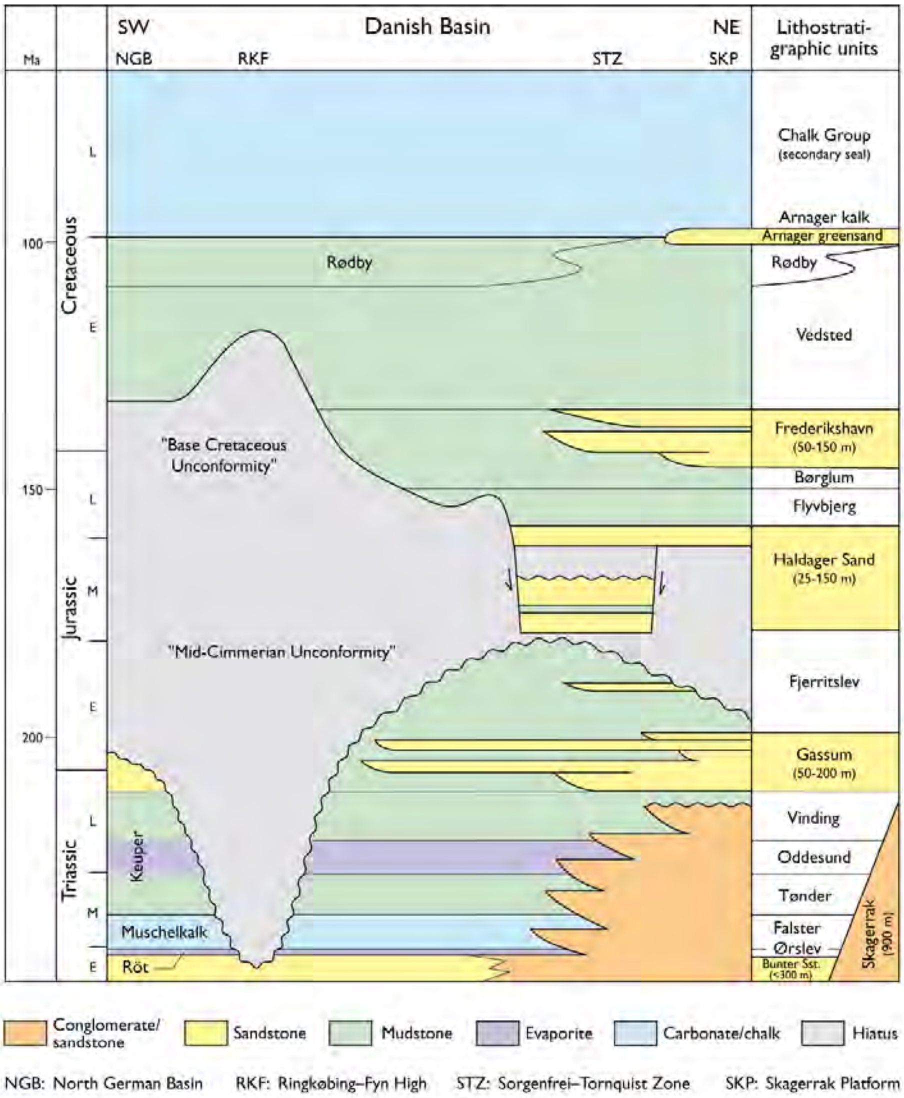

Figure 12: Simplified stratigraphy and lithostratigraphy of the sedimentary succession in the Danish Basin. (Based on Bertelsen (1980), Michelsen & Clausen (2002); Michelsen et al. (2003)).

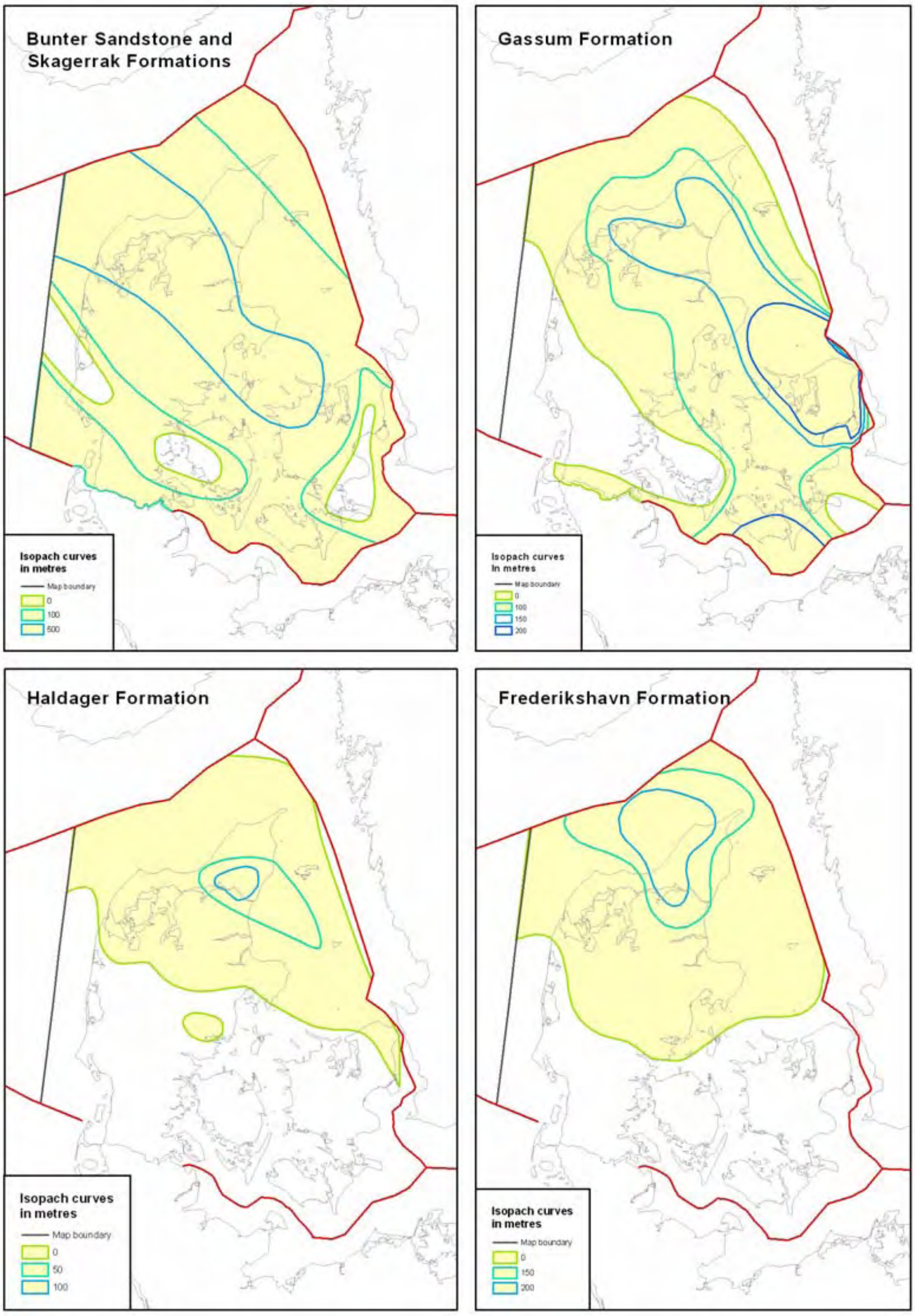

Figure 13: Identification, areal extent and thickness of four regional aquifers in Denmark.

Based on the maps in Figure 13, the volume of each of the four aquifer systems has been calculated using standard volumetric calculation methods for contoured thicknesses. In Table 8 the corresponding theoretical and effective storage capacity has been calculated using average estimates of NG, porosity and CO_2 density of 0.25, 0.2 and 0.625 t/m^3, respectively. As suggested in Vangkilde-Pedersen et al. (2008) and described in section 7.1 of the current report, the effective storage capacity has been calculated using a storage efficiency factor of 2 % based on work by the US DOE and described in Frailey (2007).

Table 8: Theoretical and effective storage capacity of four regional aquifers.

Aquifer	Volume (10^9 m^3)	Net/gross ratio	Porosity	CO_2 density (t/ m^3)	Theoretical regional CO_2 storage capacity (Gt)	Storage efficiency factor	Effective regional CO_2 storage capacity (Gt)
Bunter and Sk.	25729	0.25	0.20	0.625	804	0.02	16.1
Gassum	8557	0.25	0.20	0.625	267	0.02	5.3
Haldager	1311	0.25	0.20	0.625	41	0.02	0.8
Frederikshavn	5207	0.25	0.20	0.625	163	0.02	3.3
Total estimated regional CO_2 storage capacity (Gt)					**1275**		**25.5**

The calculated theoretical storage capacity assumes that the entire aquifer pore volume can be filled with CO_2 which is highly unlikely. It is therefore an unrealistic estimate and has only been included to demonstrate the order of magnitude of the overestimation if a realistic storage efficiency factor is not used. Using a different storage efficiency factor will of course change the effective estimate accordingly, i.e. doubling the factor will double the estimate etc.

10.2.2 Regional estimates based on trap volumes

Based on existing seismic data and depth structure maps of the Danish subsurface a number of trap structures has been identified within the four regional aquifers described above (Figure 14).

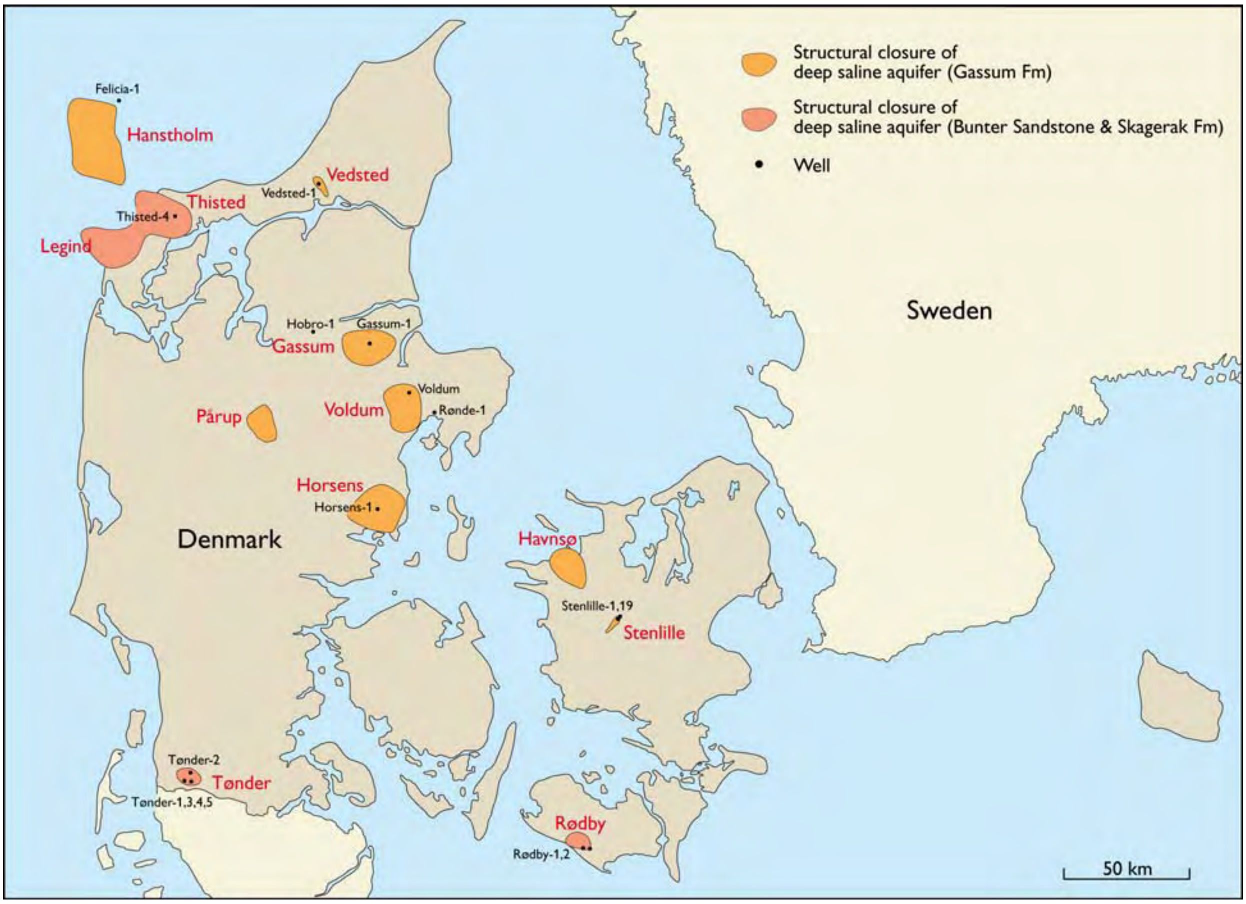

Figure 14: Identification of aquifer trap structures in regional aquifers in Denmark.

As previously described, the work by the CSLF in Bachu et al. (2007) gives no advice on values for the trap specific storage efficiency factor. In GeoCapacity we have therefore defined two different approaches for the trap specific storage efficiency factor as described in Vangkilde-Pedersen et al. (2008) and section 7.2 of the current report. One for open or semi-closed aquifer systems, the “cartoon approach” and one for closed aquifer systems, the “table approach”.

The most simple is the “cartoon approach”, assuming that the surrounding aquifer is an open or semi-closed system and suggesting rule-of-thumb storage efficiency values in the range between 3 % and 40 % for semi-closed low quality and open high quality reservoirs, respectively.

The “table approach” assumes closed aquifer systems and is based on a trap to aquifer volume ratio, total compressibility and allowable average pressure increase. This approach suggests a range of storage efficiency factors depending on depth (i.e. in fact pressure) and trap to aquifer volume ratio. For a reservoir at a depth of 2000 m, the respective storage efficiency factor for trap to aquifer volume ratios of 5, 10, 50 and 100 is 1 %, 2 %, 10 % and 20 % assuming a maximum allowable average pressure increase of 10 % of the hydrostatic pressure and a total compressibility (pore + fluid) of 10^{-4} bar^{-1}.

In Table 9 the theoretical and effective storage capacity for each of the trap structures shown in Figure 14 has been calculated using values of NG and porosity based on information from existing, but old wells or by extrapolation of nearby wells. The CO_2 density has been estimated depending on depth. The effective storage capacity has been calculated using a storage efficiency factor of 40 % corresponding to an open high quality aquifer according to the “cartoon approach”.

The calculated theoretical storage capacity assumes that the entire trapped aquifer pore volume can be filled with CO_2 which is not very likely. It is therefore not a useful estimate and has only been included to demonstrate the order of magnitude of the overestimation if a realistic storage efficiency factor is not used. Note however, that the overestimation is considerably lower than for the regional estimate due to the difference in storage efficiency factor. Using a different storage efficiency factor will of course change the effective estimate accordingly, i.e. halving the factor will halve the estimate etc.

Table 9: Theoretical and effective storage capacity of eleven trap structures.

Structure	**Volume (10^9 m^3)**	**Net/gross ratio**	**Porosity**	**CO_2 density (t/ m^3)**	**Theoretical CO_2 storage capacity (Gt)**	**Storage efficiency factor**	**Effective CO_2 storage capacity (Gt)**
Hanstholm	138.8	0.40	0.20	0.620	6.9	0.4	2.8
Gassum	31.4	0.32	0.25	0.627	1.6	0.4	0.6
Havnsoe	25.0	0.67	0.22	0.629	2.3	0.4	0.9
Horsens	29.9	0.26	0.25	0.630	1.2	0.4	0.5
Paarup	15.8	0.23	0.10	0.625	0.2	0.4	0.1
Roedby	14.2	0.18	0.24	0.620	0.4	0.4	0.2
Stenlille	1.1	0.76	0.25	0.631	0.1	0.4	0.1
Thisted	490.6	0.60	0.15	0.625	27.6	0.4	11.0
Toender	10.7	0.17	0.20	0.626	0.2	0.4	0.1
Vedsted	4.3	0.74	0.20	0.633	0.4	0.4	0.2
Voldum	30.1	0.38	0.10	0.630	0.7	0.4	0.3
Total estimated regional CO_2 storage capacity (Gt)					**41.7**		**16.7**

Table 10 summarises a range of effective storage capacity estimates for the same eleven trap structures as in Table 9 assuming confined aquifers and different values of V_{bulk}/V_{trap} and choosing the storage efficiency factor using the “table approach”. The initial pressure is assumed to be hydrostatic pressure; the allowable pressure increase is 10 % and the compressibility 10^{-4} bar^{-1}.

Table 10: Effective storage capacity using the “table approach” for storage efficiency factor.

Structure (depth in m)	**Theoretical CO_2 storage capacity (Gt)**	**Effective CO_2 storage capacity with $V_b / V_t = 1$ (Gt)**	**Effective CO_2 storage capacity with $V_b / V_t = 5$ (Gt)**	**Effective CO_2 storage capacity with $V_b / V_t = 10$ (Gt)**	**Effective CO_2 storage capacity with $V_b / V_t = 50$ (Gt)**	**Effective CO_2 storage capacity with $V_b / V_t = 100$ (Gt)**
Hanstholm(1000)	6.9	0.007	0.035	0.069	0.345	0.690
Gassum (1460)	1.6	0.002	0.012	0.023	0.117	0.234
Havnsoe (1500)	2.3	0.003	0.017	0.035	0.173	0.345
Horsens (1506)	1.2	0.002	0.009	0.018	0.090	0.181
Paarup (1550)	0.2	0.000	0.002	0.003	0.016	0.031
Roedby (1125)	0.4	0.000	0.002	0.005	0.023	0.045
Stenlille (1507)	0.1	0.000	0.001	0.002	0.008	0.015
Thisted (1203)	27.6	0.033	0.166	0.332	1.660	3.320
Toender (1615)	0.2	0.000	0.002	0.003	0.016	0.032
Vedsted (1898)	0.4	0.001	0.004	0.008	0.038	0.076
Voldum (1757)	0.7	0.001	0.006	0.012	0.061	0.123
Total (Gt)	**41.7**	**0.051**	**0.255**	**0.509**	**2.546**	**5.092**

10.2.3 Comparison of methods for deep saline aquifers

Theoretical versus effective
Theoretical capacity estimates assuming that the entire available pore volume can be filled with CO_2 are regarded unrealistic. For the Danish Basin a theoretical storage capacity of 1275 Gt has been calculated based on the bulk volume of four regional aquifers. This should be compared to an effective storage capacity of 25.5 Gt using a storage efficiency factor of 2 %.

Similarly a theoretical storage capacity of 41.7 Gt has been calculated for eleven trap structures identified in the Danish Basin. This should be compared to an effective storage capacity of 16.7 Gt using a storage efficiency factor of 40 %.

Bulk volume versus trap volume estimates
An effective storage capacity of 25.5 Gt has been calculated for the Danish Basin based on the bulk volume of four regional aquifers. In the same area, eleven individual trap structures have been identified. The effective storage capacity of these eleven structures is 16.7 Gt based on the trap aquifer volumes and using a storage efficiency factor of 40 %. These two estimates are comparable, especially taking into consideration that more structures exist in the Danish Basin, but has not been evaluated. This indicates that using a storage efficiency factor of 2 % for regional bulk volume estimates together with the assumptions of NG and porosity (0.25 and 0.20, respectively) is reasonable for initial and rough estimates in the said region.

The “cartoon approach” versus the “table approach”
As it appears from Table 9 and Table 10 the storage capacity is considerably lower assuming confined aquifers and using the “table approach” compared to assuming high quality open aquifers and using the “cartoon approach”. Assuming high quality open aquifers results in a storage efficiency factor of 40 % using the “cartoon approach”. This gives a total effective

storage capacity of 16.7 Gt for the eleven trap structures identified in the Danish Basin. Assuming confined aquifers, 10 % allowable pressure increase and compressibility of 10^{-4} bar^{-1} result in storage efficiency factors ranging from 0.15 % to 15 % for values of V_{bulk}/V_{trap} from 1 to 100. This gives a range of total effective storage capacity from 0.05 to 5 Gt for the eleven traps.

Assuming 25 % allowable pressure increase instead of 10 % and a V_{bulk}/V_{trap} ratio of 100 will on the other hand result in an average storage efficiency factor of 36.6 % and a total effective storage capacity of 12.7 Gt using the table approach. Assuming 50 % allowable pressure increase and a V_{bulk}/V_{trap} ratio of 50 will give the same result.

Correspondingly assuming a low quality reservoir with limited connectivity to the surrounding aquifer will result in a storage efficiency factor of 5 % and a total effective storage capacity for the eleven trap structures of 2.1 Gt using the “cartoon approach”. This is comparable to the total effective storage capacity of 2.5 Gt obtained using the “table approach” assuming 10 % allowable pressure increase and a V_{bulk}/V_{trap} ratio of 50.

10.3 Hydrocarbon fields

Two different methods have been used for estimating hydrocarbon field storage capacity. The CSLF/GESTCO method has been used for most estimates in the database as described in section 8.1. An alternative model has been developed by IFP (Bossie-Codreanu, 2008) and is described in section 8.2.

10.3.1 Comparison of methods for hydrocarbon fields

Only a few countries have been able to provide the relatively detailed data input required for running the model for storage capacity estimation and EOR in oil fields. The model has been used for 2 Polish oil fields, 1 Czech R. oil field and 2 Danish oil fields. The second column in Table 11 shows the storage capacity corresponding to the oil volume in the fields and calculated using the CSLF/GESTCO formula. Thus, the storage capacity corresponding to the gas volume of the fields is not included for this comparison. The third column shows the storage capacity calculated using the model. It appears from the results, that the estimated storage capacity is higher (except for Kamien-Pom.) with the EOR model compared to the CSLF/GESTCO method. This corresponds well to the fact that the model predicts a much higher oil recovery factor (1.4-2.1 times higher) with CO_2 EOR than originally assumed without CO_2 EOR in the estimates of UR_p for the CSLF/ GESTCO estimate. At the same time the model predicts a lower (and perhaps more realistic) oil – CO_2 replacement factor and consequently the capacity estimates are “only” 1.1-1.3 times higher with the model.

Table 11: Comparison of estimates for database and estimates using detailed model.

Oil field and country	**CO_2 storage capacity calculated using CSLF/GESTCO methodology (Mt)**	**Assumed R_f associated with CSLF/GESTCO estimate**	**CO_2 storage capacity calculated using EOR model (Mt)**	**Calculated R_f associated with the EOR model**
Kamien-Pom. (Poland)	2.2	0.31	0.9	0.43
BMB (Poland)	11	0.16	12.6	0.33
Hrusky (Czech R.)	1.1	-	1.4	-
South Arne (Denmark)	24	0.35	32	0.59
Dan (Denmark)	90	0.28	110	0.59

The EOR model assumes that the oil fields are not fractured, but both Kamien-Pom. and BMB are fractured fields and South Arne has a few natural fractures. Furthermore the model does not take horizontal wells into consideration, but South Arne and Dan have horizontal production wells. Both may have an effect on the model results. Further explanation on the differences between the two methods is given below.

The two models (the CSLF/GESTCO and the IFP EOR) both aim to quantify the potential CO_2 storage capacity of depleted oil hydrocarbon reservoirs. Therefore, both these models can be considered as "simple" formula models which try to capture an "approximation" of a possible storage capacity. Nevertheless, between these models several differences exist, namely:

- The CSLF model is a "volumetric" model, which assumes that CO_2 will replace a produced volume of oil. No consideration is given to the possible EOR benefit which could come from a CO_2 injection, except as a bulk coefficient which is averaged in "ad-hoc". No justification is asked by the model for the definition of the "recovery factor" which determines the volume of oil which the CO_2 will replace.
- The IFP model considers the EOR option explicitly. That is why three CO_2 volumes are actually calculated (before breakthrough of the CO_2, during the CO_2 sweeping and post production during the filling up of the reservoir). Furthermore is assumes miscibility displacement by CO_2 and vertical wells only (no horizontal wells, no fractured reservoirs).

Thus the CSLF model assumes a recovery factor and deduces a CO_2 storage volume, whereas the IFP model calculates a recovery factor and its associated CO_2 storage at different stages of that process.

As such, in case of CO_2 sequestration in a hydrocarbon reservoir, a unique standard model is difficult to define. All cases will be different. One could use an oil reservoir without oil production, thus not accounting for the CO_2 trapped during the EOR stage or one could use an oil reservoir with EOR. The two storage values will be very different, given the fact that pressure drop, trapping characteristics, and essentially, partitioning of the CO_2 between the two phases (oil and water) will affect the overall compressibility of the system and thus the ultimate volume of CO_2 stored for an allowed pressure differential.

The fluid production during the CO_2 injection is a common problem to gas, oil and coal storage problems. If for gas reservoirs the problem is less drastic (unless EGR is sought after), it is a major problem when considering oil reservoirs (for which the EOR issue is of prime economic importance) and for coal (for which the dewatering stage, along with CH_4 production, is mandatory before even attempting to inject the CO_2).

In conclusion, the standardization is impossible if boundary conditions of the problem are not given. The two models work under different assumptions. Sometimes results are close, especially if the benefit of the EOR is limited. More work is needed in order to be able to adequately describe a "standard" approach when considering depleted hydrocarbon reservoirs (ex. boundary conditions).

10.4 Coal fields

The CO_2 storage capacity in coal fields in the GeoCapacity database are calculated using the methodology described in the GESTCO reports on CO_2-ECBMR potential for Belgium (van

Tongeren & Laenen, 2001), Germany (May, 2003) and Netherlands (van Bergen & Wildenborg, 2002) and also complies with the descriptions of the CSLF in Bachu et al. (2007).
Using the formula described in section 9 with PGIP for individual fields and estimation of parameters will yield almost effective estimates that can be improved using reservoir simulators like CoalSeq if sufficient and reliable input data can be obtained.

Using the formula for entire basins and values of coal bed parameters averaged over the whole basin result in capacity estimates being partly theoretical and partly effective.

Using the formula with GIP instead of PGIP will provide theoretical capacity estimates

10.4.1 Comparison of methods for coal fields

Three countries have calculated three different levels of CO_2 storage capacity estimates in coal fields, see Table 12. First the capacity of regional basins was calculated using PGIP and averaged basin scale parameter assumptions. Then the capacity of mining areas or coal field areas was calculated using PGIP and averaged parameter assumptions. Finally effective capacity of selected coal fields was calculated using PGIP and estimated or modelled parameters for individual fields. The results demonstrate the principle of the resource-reserve pyramid in the sense that the estimates get smaller and smaller while the level of confidence is increasing.

Table 12: Comparison of theoretical and effective storage estimates for coal fields.

Country	**CO_2 storage capacity of regional basins calculated using PGIP and averaged basin scale parameter assumptions (Mt)**	**CO_2 storage capacity of coal field areas calculated using PGIP and averaged parameter assumptions (Mt)**	**Effective CO_2 storage capacity of selected coal fields calculated using PGIP and estimated or modelled parameters for individual fields (Mt)**
Czech R.	380	118	54
Hungary	224	68	15
Poland	1254	415	239

11 REFERENCES

Bachu, S. and Adams, J.J. 2003: Sequestration of CO_2 in geological media in response to climate change: Capacity of deep saline aquifers to sequester CO_2 in solution. *Energy Conversion and Management*, **44**(20), 3151-3175.

Bachu, S., Bonijoly, D., Bradshaw, J., Burruss, R., Christensen, N.P. Holloway, S., and Mathiassen, O.M. 2007: Estimation of CO_2 Storage Capacity in Geological Media – Phase 2. Work under the auspices of the Carbon Sequestration Leadership Forum (www.cslforum.org).

Bech, N. and Larsen, M. 2005: Storage of CO_2 in the Havnsø aquifer – a simulation study. A CO2STORE contribution. Danmarks og Grønlands Geologiske Undersøgelse Rapport 2005/9.

Bergen van F., Wildenborg T. 2002: Inventory of storage potential of Carboniferous coal layers in the Netherlands - TNO Report NITG 02-031-B (GESTCO), Utrecht.

Bertelsen, F. 1980: Lithostratigraphy and depositional history of the danish Triassic. Geological Survey of Denmark. Series B 4, 59 pp.

Bossie-Codreanu, D. 2008: GeoCapacity economic use of CO_2 in hydrocarbon fields. EU GeoCapacity deliverable D19.

Bradshaw, J., Bachu, S., Bonijoly, D., Burruss, R., Holloway, S., Christensen, N.P. and Mathiassen, O.M. 2006: CO_2 storage capacity estimation: issues and development of standards. Work under the auspices of the Carbon Sequestration Leadership Forum (www.cslforum.org).

Brook, M., Shaw, K., Vincent, C. and Holloway S. 2003: Gestco case study 2a-1: Storage Potential of the Bunter Sandstone in the UK sector of the southern North Sea and the adjacent onshore area of Eastern England. British Geological Survey Commissioned Report, CR/03/154. 37pp.

Chadwick, A., Arts, R., Bernstone, C., May, F., Thibeau, S. and Zweigal, P. 2006. Best practice for the storage of CO_2 in saline aquifers. Observations and guidelines from the SACS and CO_2STORE projects.

Chiaramonte, L., Zoback, M., Friedmann, J., and Stamp, V. 2006. CO_2 sequestration, fault stability and seal integrity at Teapot Dome, Wyoming. In: 8th International Conference on Greenhouse Gas Control Technologies. Trondheim, Norway: Norwegian University of Science and Technology.

Claridge, E. L. 1972: Prediction of Recovery in Unstable Miscible Flooding. Soc. Pet. Eng. J.

Dykstra, H. and Parsons, R. L. 1950: Secondary Recovery of Oil in United States. API, Washington.

Frailey, S. 2007: Estimation of the Storage Efficiency Factor for Saline Formations. Appendix 1 in Methodology for Development of Carbon Sequestration Capacity Estimates. Appendix A in Carbon Sequestration Atlas of the United States and Canada. U.S. Department of Energy Office of Fossil Energy, National Energy Technology Laboratory.

Goodyear, S., Hawkyard, I., Masters J. & Woods C. 2005: Subsurface issues for CO_2 flooding of UKCS reservoirs. DTI's Improved Oil recovery Research Dissemination Seminar, 25.

Hadlow, R. E. 1992: Update of Industry Experience with CO_2 Injection. SPE 24928, p 10.

Hadlow, R. E. 1992: Update of Industry Experience with CO_2 Injection. SPE 24928, p 10.

Hawthorne, R. G. 1960: Two-Phase Flow in Two Dimensional Systems – effects of Rate, Viscosity and Density of Fluid Distribution in Porous Media. Trans. AIME.

Kiode, H.G., Y. Tazaki, Y. Noguchi, S. Nakayama, M. Lijima, K. Ito and Y. Shindo. 1992: Subterranean containment and long-term storage of carbon dioxide in unused aquifers and in depleted natural gas reservoirs. *Energy Conversion and Management*, **33** (5-8), 619-626.

Kirk, K. 2006. The potential of large UK offshore gas fields for storing CO_2 emissions from E.ON power stations. British Geological Survey Commissioned Report, CR/06/011N. 41pp

Koval, E. J. 1963: A method for predicting the Performance of Unstable Miscible Displacement in Heterogeneous Media. Soc. Pet. Eng. J.

May F. 2003: CO_2 storage capacity in unminable coal beds i Germany - GESTCO Project report, Bundesanstalt fűr Geowissenschaften und Rohstoffe, Hannover.

Michelsen, O. & Clausen, O.R. 2002: Detailed stratigraphic subdivision and regional correlation of the southern Danish Triassic succession. Marine and Petroleum Geology 19, 563–587.

Michelsen, O., Nielsen, L.H., Johannessen, P.N., Andsbjerg, J. & Surlyk, F. 2003: Jurassic lithostratigraphy and stratigraphic development onshore and offshore Denmark. In: Ineson, J.R. & Surlyk, F. (Eds.) The Jurassic of Denmark and Greenland. Geology of Denmark Survey Bulletin 38.

Peneloux, A., Rauzy, E. and Fréze, R. 1982: A consistent correction for Redlich-Kwong-Soave volumes, *Fluid Phase Equilibria* **8**, 7-23.

Raimondi, P. and Torcaso, M. A. 1964: Distribution of the Oil Phase Obtained upon Imbibition of Water. Soc. Pet. Eng. J.

RECOPOL workshop 2005: Reduction of CO_2 emission by means of CO_2 storage in coal seams in the Silesian Coal Basin in Poland - Workshop Szczyrk, Poland, March 2005 (abstract book).

Schuppers, J.D., Holloway, S., May, F., Gerling, P., Bøe, R., Magnus, C., Riis, F., Osmundsen, P.T., Larsen, M., Andersen, P.R. and Hatzyannis, G. 2003. Storage capacity and quality of the hydrocarbon structures in the North Sea and the Aegean region. TNO-report NITG 02-020-B.

Shaw, J. and Bachu, S. (2002): Screening, evaluation, and ranking of oil reservoirs suitable for CO_2-flood EOR and carbon dioxide sequestration. J. Can. Petrol. Tech., Vol. 41, No. 9, p51-61.

Span R. and Wagner W. 1996: A new equation of state for carbon dioxide covering the fluid region from the triple-point temperature to 1100 K at pressures up to 800 MPa. Journal of Physical Chemistry Reference Data, Vol. 25, No. 6, 1509-1596.

Tongeren van, P.C.H., Laenen B. 2001: Coalbed methane potential of the Campine Basin (N. Belgium) and related CO_2-sequestration possibilities, GESTCO WP Report, VITO.

Van der Meer, L.G.H. 1993: The Conditions Limiting CO_2 Storage in Aquifers, Energy Convers. Mgmt 34 (9-11) 959-966

van der Meer, L.G.H., and van Wees, J.D. 2006: Limitations of the Storage Pressure in Finite Saline Aquifers and the effects of the CO_2 Solubility on the Storage Pressure, SPE 103342.

van der Meer, L.G.H. and J.D.van Wees, 2006(2): Effects of CO_2 solubility on the long-term fate of CO_2 sequestered in a saline aquifer, The Leading Edge, October 2006, 1276.

Vangkilde-Pedersen, T., Neele, F., van der Meer, B., Egberts, P., Wójcicki, A., Bossie-Codreanu, D., Le Nindre, Y.M., Barthélémy, Y. 2008: Storage capacity standards. EU GeoCapacity deliverable D24.

Vosgerau, H., Kirk, K.L., von Dalwigk, I. & Vangkilde-Pedersen, T. 2008: Site selection criteria. EU GeoCapacity deliverable D23.

Zhou, Q., Birkholzer, J.T., Tsang, C.-F. and Rutqvist, J. 2008: A method for quick assessment of CO_2 storage capacity in closed and semi-closed saline formations. *International Journal of Greenhouse Gas Control, Volume 2, Issue 4, October 2008, Pages 626-63*.