

# **CO2StoP Final Report**

Assessment of CO<sub>2</sub> storage potential in Europe  
European Commission Contract No ENER/C1/154-2011-SI2.611598

Niels Poulsen, Sam Holloway, Filip Neele, Nichola Ann Smith & Karen Kirk

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## Assessment of CO2 storage potential in Europe European Commission Contract No ENER/C1/154-2011-SI2.611598

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Project title:  
**Assessment of CO<sub>2</sub> storage potential in Europe**



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ENER/C1/154-2011-SI2.611598

Project acronym:  
**CO2StoP**

Instrument: Specific Targeted Research Project  
Start date of project: January 2012 (Dec. 19<sup>th</sup> 2011)  
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**CO2StoP Final Report**  
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<b>Dissemination Level</b>		
<b>PU</b>	Public	<b>X</b>
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## 1 INTRODUCTION

### 1.1 Foreword

CO2StoP is the acronym for the project CO<sub>2</sub> Storage Potential in Europe project. The CO2StoP project started on January 2012 (Dec. 19<sup>th</sup> 2011) and ended in December 2013.

Results of the study are provided in:

- A Database of CO<sub>2</sub> storage locations throughout Europe,
- a Database Analysis/Interrogation Tool,
- a tool to compute storage capacities and injection rates (“StoreFit”),



- a manual to both the database analysis/interrogation tool and the StoreFit tool,
- an Interim Report,
- this Final Report,
- a power point presentation, and, finally,
- an executive summary.

These reports are written for non-technicians and the technical and geological results are intended to provide a first solid foundation upon which the storage capacity for CCS and EOR can be judged and, hopefully, be declared sufficiently sound to warrant widespread application in Europe. 27 countries<sup>1</sup> are covered in the CO2StoP project. Latvia was covered by the Estonian-Latvian border project. Albania and Bosnia-Herzegovina dropped out of the project.

## 1.2 Legal notice

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## 2 WP1: HARMONISED METHODOLOGY

### 2.1 Introduction

It was stated in the call for tenders that the storage capacity assessment data is to be for policy making purposes. Therefore we have provided a tool to help answer the following two questions which we believe will allow policymakers to assess the potential role of CCS in a portfolio of greenhouse gas mitigation options:

- How much CO<sub>2</sub> storage capacity can be relied on?
- Where is this CO<sub>2</sub> storage potential?

The database that underlies the CO<sub>2</sub> storage capacity assessment contains the data fields necessary to answer these questions. It also contains data fields that allow the assessment of geological risks (the chances of successful storage) in each unit of assessment.

A Data Analysis System has been developed to analyze the complex data in the database, and a GIS has been produced that is capable of:

- Displaying the location of each potential geological storage formation
- Displaying the location of individual units of assessment within those formations
- Displaying any further subdivisions of these units (daughter units i.e. hydrocarbon fields and potential structural traps in saline aquifers)
- Displaying selected attributes of the storage unit

Finally, formulae have been provided that will enable the necessary calculations of storage resources to be carried out. Application of a cost model is outside the scope of the current project.

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<sup>1</sup> Member States: Austria, Belgium, Bulgaria, Croatia, Czech Republic, Denmark, Estonia, France, Germany, Greece, Hungary, Ireland, Italy, Lithuania, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Spain and UK.  
Non Member States: FYROM, Norway, Serbia, Switzerland.



## 2.2 Introduction to CO<sub>2</sub> storage resource assessment

A resource can be defined as anything potentially available and useful to man. As will be described below, pore space in deeply buried reservoir rocks is a resource that can be used for CO<sub>2</sub> storage. It is of the utmost importance to be aware that the presence of a resource does not indicate that any fraction of it can be exploited economically now or in the future.

A reserve can be defined as that part of a resource that is available to be exploited economically now using currently available technology. Thus in order to move from a resource estimate to a reserve estimate a whole series of technical, economic, legal and socioeconomic criteria have to be applied to the resource to identify the fraction of the resource that can actually be economically exploited in a particular jurisdiction using presently available technology. Consequently, a very high level of technical assessment is required to demonstrate the existence of a CO<sub>2</sub> storage reserve. And the resources required achieving the level of technical assessment required to define CO<sub>2</sub> storage reserves are in most cases only available within a demonstration or commercial storage project. For these reasons, it has not been possible to define any CO<sub>2</sub> storage reserves in the present project. Nevertheless, the goal of the project is to provide a means not only of estimating the total CO<sub>2</sub> storage resource available in a jurisdiction but also to estimate the fractions of this resource that are available when certain technical constraints are applied to it. The idea was to move as far in the direction of a reserves estimate as possible because applying these extra constraints gives policymakers and other stakeholders a more useful idea of the realistic potential for CCS in Europe than a simple resource estimate.

### 2.2.1 Storage mechanisms

Carbon dioxide can be retained in reservoir rocks by the following mechanisms:

- Structural and stratigraphic trapping, in which gaseous or supercritical CO<sub>2</sub>, which would otherwise migrate due to advective forces and/or its buoyancy, is immobilised by low-permeability barriers (cap rocks and/or lateral seals).
- The development of a residual saturation of gas or supercritical phase CO<sub>2</sub> trapped in the pore space by capillary forces.
- Dissolution into the pore fluids present within the reservoir rock
- Precipitation of carbonates or other carbon-rich minerals – a process that starts with the dissolution of aluminosilicate minerals in the rock framework by pore waters acidified by dissolved CO<sub>2</sub>.
- Adsorption onto the surfaces of carbon-rich grains within, for example, shales or coals

In typical porous and permeable saline water-bearing reservoir rocks (commonly described as deep saline aquifers in the CCS literature), adsorption onto carbon-rich surfaces within the rock matrix is generally considered a relatively unimportant storage mechanism, because few such surfaces are present. Moreover, both mineral reaction and the dissolution of CO<sub>2</sub> into pore fluids are also considered to be relatively unimportant on injection timescales (say 50 years or so) because the kinetics of these processes are relatively slow (van der Meer & van Wees 2006). Therefore, they are unlikely to greatly affect storage capacity.

Therefore, it is commonly argued that over injection timescales the vast majority of the CO<sub>2</sub> retained in conventional reservoir rocks will either be stored as a gas or supercritical fluid in the fluid-filled pore spaces between the grains that make up the matrix of the rock and/or any fluid-filled fractures. Moreover, the vast majority of the CO<sub>2</sub> will be trapped either in structural and/or stratigraphic traps or by capillary forces as a residual saturation (Bachu et al. 2007). Many storage



capacity estimates focus on these two trapping mechanisms on the basis that the uncertainties in the estimate caused by other factors are far greater than those caused by ignoring dissolution, mineral reaction and adsorption. They also ignore the fluid-filled volume in fractures and focus on pore space as the location for CO<sub>2</sub> storage, on the grounds that the void space in fractures is extremely low compared to that in pore space.

### 2.2.2 Geological and physical constraints on CO<sub>2</sub> storage capacity

Each jurisdiction contains a given amount of pore space within its subsurface. The total resource of pore space that is potentially available for CO<sub>2</sub> storage in a jurisdiction is that part of its total pore space that can be filled with, and will retain, injected CO<sub>2</sub>. Geology and physics dictate that this will be far less than the total pore space in a jurisdiction. For example:

- Heterogeneity in the reservoir rock and gravity effects means that the injected CO<sub>2</sub> will not contact all the pore space within the reservoir rock.
- There is an irreducible water saturation that will always remain within the pore space of the reservoir rock in areas that are contacted by [water-saturated] CO<sub>2</sub>. This residual pore water may become saturated with dissolved CO<sub>2</sub> but it cannot be displaced by free gas-phase or supercritical phase CO<sub>2</sub>.
- Even where injected CO<sub>2</sub> enters pore space, a trapping mechanism is needed to retain it. This may not be present.

These limitations mean that only a small fraction of the total resource of pore space in a jurisdiction can be filled with CO<sub>2</sub>. Whilst geology varies greatly between jurisdictions, the underlying physical processes that dictate how much of the total pore space is theoretically available for CO<sub>2</sub> storage does not, i.e. they apply in all jurisdictions. Therefore, it is possible to define a common methodology that can be used to estimate the fraction of the total resource of pore space that could be used for CO<sub>2</sub> storage in any jurisdiction. If appropriate CO<sub>2</sub> densities at reservoir conditions are applied to this volume, this allows estimation of the **theoretical CO<sub>2</sub> storage resource**, i.e. the mass of CO<sub>2</sub> that could be stored in the fraction of the total resource of pore space that can be filled with CO<sub>2</sub>.

### 2.2.3 Technical, legal, economic and social constraints on CO<sub>2</sub> storage capacity

In practice, only a fraction of the theoretical CO<sub>2</sub> storage resource in any given jurisdiction can actually be utilised – for a variety of technical, economic, legal and social reasons. For example, because:

- Part of the theoretical CO<sub>2</sub> storage resource may not be accessible with current drilling and injection technologies.
- It may be illegal or socially unacceptable to store CO<sub>2</sub> in certain volumes of otherwise suitable pore space, e.g. in places where it could affect potable water supplies or places where it is not confined by a structural or stratigraphic trap.
- It may not be considered practical to use certain engineering techniques, e.g. pressure management wells, to reduce the build-up of the reservoir pore fluid pressure in the storage reservoir. This may mean that not all the pore space that theoretically could be contacted by CO<sub>2</sub> can actually be accessed before limiting pressures, e.g. pressures that might fracture the cap rock, are reached.
- An optimal sweep of the reservoir rock by the injected CO<sub>2</sub> might not be possible with a reasonable number of injection wells, meaning that a less than optimal mass of CO<sub>2</sub> would be stored per unit volume.





- The injectivity of the storage reservoir (the ability of a reservoir to receive injected fluid) may be too low for injection to be practical.

One or more of these constraints may be applied to the theoretical CO<sub>2</sub> storage resource to produce a resource estimate that is of more use to domestic or other policymakers. For example, the USGS (Brennan et al. 2009) estimates the **technically accessible CO<sub>2</sub> storage resource**, i.e. the fraction of the theoretical storage resource that can be accessed using all currently available technologies (regardless of cost), excluding that part of the resource that contains water with less than 10,000 ppm dissolved solids (potable water) and that part of the resource above 914 m (where stored CO<sub>2</sub> is likely to be in the gas phase and thus CO<sub>2</sub> storage density is likely to be low).

Unfortunately different jurisdictions may wish to produce estimates of different fractions of the theoretical CO<sub>2</sub> storage resource, for example because they have different laws affecting CO<sub>2</sub> storage. Consequently they commission capacity studies covering different subsets of the theoretical storage resource. This means there is not necessarily a common basis for comparison between national or jurisdictional CO<sub>2</sub> storage resource estimates. If resource estimates are to be comparable across jurisdictions, they need to apply a common set (or sets) of geological and/or physical, technical, legal, political and social constraints. They also need to use a common calculation methodology for the resource present in saline aquifers and hydrocarbon fields.

On the positive side, any subset of the theoretical CO<sub>2</sub> storage resource can be derived from a single geological data set provided it is comprehensive enough. However, data quality and budgets may limit the accuracy, the area studied or the types of storage potential considered (e.g. hydrocarbon fields, deep saline aquifers) in a resource estimate. A sufficiently large budget and access to suitable data are pre-requisites for producing a satisfactory resource assessment.

#### 2.2.4 Going beyond resource assessment

The questions that any CO<sub>2</sub> storage capacity study sets out to answer may not only be questions about the resource present in a subset or subsets of the theoretical CO<sub>2</sub> storage resource. They may also relate to the chances of successful long-term storage or the cost of storage in a given unit of assessment. These additional questions may be answered by storage risk assessments and the application of cost and economic models. Thus geological risk data needs to be collected.

### 2.3 CO<sub>2</sub> Storage resource assessment in CO2StoP

In the CO2StoP project, the pore space in a jurisdiction is subdivided into reservoir formations. These are mappable bodies of rock that are continuous in the subsurface and which are both porous and permeable. Each reservoir formation contains one or more storage units. A storage unit is defined as a part of a reservoir formation that is at depths greater than 800 m and which is covered by an effective cap rock. These storage units are considered to have potential for CO<sub>2</sub> storage and they form the basis of the CO<sub>2</sub> storage estimates made in the CO2StoP project. Each storage unit may contain one or more daughter units. Daughter units are defined as structural or stratigraphic traps which have the potential to immobilise CO<sub>2</sub> within them, e.g. domes in saline water-bearing parts of the reservoir rock that are completely sealed by cap rocks (aquifer daughter units), or proven oil and gas fields (hydrocarbon field daughter units). Daughter units have the potential to be able to store CO<sub>2</sub> at higher saturations than the remainder of a storage unit, so their storage potential can be estimated separately in CO2StoP.



The methods used to produce resource estimates are outlined below, and discussed more fully in Section 4 of the report.

### **2.3.1 Estimating the Technically Accessible CO<sub>2</sub> Storage Resource**

The CO2StoP calculation engine (see below) is capable of producing a resource estimate that is very similar to the Technically Accessible CO<sub>2</sub> Storage Resource estimated by the US Geological Survey (Brennan et al. 2009), i.e. the fraction of the theoretical storage resource that can be accessed using all currently available technologies regardless of cost. The IEA has recommended that the first step in all CO<sub>2</sub> storage resource estimates should be to estimate the TASR (Heidug, 2013).

This estimate is produced via the following steps:

1. Estimate the pore volume of all storage units
2. Estimate the pore volume of all aquifer daughter units within each 'parent' storage unit
3. Subtract the volume of the aquifer daughter units from that of their parent storage units
4. Estimate the density of CO<sub>2</sub> at storage unit reservoir conditions
5. Multiply the estimated pore volume by the estimated CO<sub>2</sub> density at reservoir conditions
6. Multiply the resulting mass of CO<sub>2</sub> by a storage efficiency factor<sup>2</sup>
7. Sum the results from all storage units
8. Add the estimated storage capacity of the hydrocarbon fields (see section 2.3.4)

This estimate differs in one main respect from the TASR estimated by the USGS method:

It adds the storage capacity of hydrocarbon fields to that of the saline aquifers. This has to be done because the pore volume of the hydrocarbon fields is not provided in the database, so it cannot be subtracted from the pore volume of the storage units before their storage capacity is estimated.

There are other minor differences in the constraints and assumptions. Nevertheless, it is considered that two methods produce results that are sufficiently similar to allow them to be compared.

At present, the user needs to enter the storage efficiency factor to be used. It is recommended that, in future, additional code is written to enable the storage efficiency factor for each storage unit to be estimated by the method shown in Blondes et al. 2013.

In a European context, the TASR should only be used for extra-European international resource comparisons because it is certain that the TASR is several times larger than the practical CO<sub>2</sub> storage capacity. Consequently quoting the TASR can be misleading to policymakers, and the press, who may not grasp the critical distinction between resource and reserve estimates.

### **2.3.2 Estimating the CO<sub>2</sub> storage resource assuming pressure management is not implemented**

This is a subset of the TASR, calculated by a different method. Theoretically, pressure management can be undertaken by drilling additional wells into a storage unit and producing some of the pore fluid (brine) that is present in the saline aquifer. This would create space for the injected carbon dioxide and would reduce the pressure build-up in the storage unit. However, this could be very expensive and would require the treatment or disposal of the produced brine. Therefore the

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<sup>2</sup> The storage efficiency factor of a reservoir is an estimate of the fraction of the total pore space within that reservoir that can be occupied by carbon dioxide. This factor is used typically during the screening phase to obtain an expert's opinion on the storage capacity of a reservoir, when insufficient data is available to produce a more exact capacity estimate.



underlying assumption in this type of estimate is that fluid will not be produced from saline aquifer CO<sub>2</sub> storage units to relieve the pressure build-up that is caused by injecting CO<sub>2</sub> into them.

This estimate lies further towards the reserve end of the resource-reserve spectrum than the TAsR because it applies an economic constraint (no pressure management wells).

The estimate is produced via the following steps:

1. Estimate the pore volume of all storage units
2. Estimate the permissible pressure increase and thus the permissible pressure limit in each storage unit
3. Estimate the compressibility of the initial pore fluid (brine)
4. Estimate the compressibility of the storage unit rock matrix (actually the amount by which it will expand at the permissible pressure limit)
5. Estimate the pore space available in the storage unit at the permissible pressure limit as a result of the compressibility of the brine and rock matrix
6. Estimate the CO<sub>2</sub> density at the permissible reservoir pressure and storage unit temperature
7. Multiply the pore space available by the CO<sub>2</sub> density at the permissible reservoir pressure and storage unit temperature
8. Sum the results from all storage units
9. Add the estimated storage capacity of the hydrocarbon fields (see section 2.3.4).

This type of estimate produces a result that is closer to the practical storage capacity in Europe than the TAsR, but it does not take account of any possible regulation that may require the CO<sub>2</sub> injected into saline aquifers to be immobilised within a structural or stratigraphic trap.

A shortcoming of this type of estimate as currently implemented is that the limiting pressure is an average pressure assumed to be distributed evenly throughout the entire storage unit. In practice, pressure will vary across the storage unit during the injection period, being greater than average around the injection well(s).

### **2.3.3 Estimating the CO<sub>2</sub> storage resource in structural and stratigraphic traps**

The CO<sub>2</sub>StoP calculation engine allows a probabilistic estimate of the CO<sub>2</sub> storage resource in structural and stratigraphic traps to be calculated by the following steps:

1. Estimate the CO<sub>2</sub> storage capacity of all saline aquifer daughter units, using either a storage efficiency method (Section 2.3.1) or a pressure capacity method (Section 2.3.2)
2. Sum the results from all daughter units
3. Add the estimated storage capacity of the hydrocarbon fields (see section 2.3.4).

### **2.3.4 Estimating the CO<sub>2</sub> storage resource in hydrocarbon fields**

The CO<sub>2</sub>StoP calculation engine estimates the CO<sub>2</sub> storage resource in hydrocarbon fields based on the assumption that the space that will be available for CO<sub>2</sub> storage in hydrocarbon fields is the space occupied by the Ultimately Recoverable Reserves (URR) of hydrocarbons under reservoir conditions

This method was used because the necessary data is either available or can be estimated for most European hydrocarbon fields.

The estimate is produced via the following steps:

1. Enter or estimate the URR of the oil in the hydrocarbon field



2. Determine its volume at reservoir conditions by dividing the URR oil by the oil formation volume factor
3. Enter or estimate the URR of any free gas in the hydrocarbon field
4. Determine its volume at reservoir conditions by dividing the URR free gas by the gas formation volume factor
5. Multiply the above volumes by the density of CO<sub>2</sub> at the initial reservoir conditions

It should be borne in mind that there are many factors that could affect the accuracy of this estimate. For example, smaller fields may not be considered for CO<sub>2</sub> storage, not all the URR may be produced from the field, water may enter the field as the hydrocarbons are produced, enhanced oil recovery may mean that more oil is produced than the estimated URR.

## 2.4 Comments on the methodology

One advantage of the methodology is that the resource is broken down into assessable geological volumes (storage units and daughter units). This means that it is possible to further develop the data by writing an assessment report for any storage unit. This should provide a full basis for the data and judgements held for that storage unit in the database. However, time and budget meant that this was not possible within the current project.

## 2.5 The CO2StoP methodology

The methodology that has been implemented for the project has involved the development of the CO2StoP Data Analysis system and the CO2StoP GIS. The CO2StoP Data Analysis/Interrogation Tool is made up of two main parts, these being the CO2StoP Database which is designed to hold and process the project data from all project partners and the CO2StoP StoreFit calculation engine which is used for stochastic analysis of the data. Further detail on the Data Analysis/Interrogation Tool can be found in Section 5.4 The CO2StoP GIS is used to view and analyse the data contained in the CO2StoP Database and export data for use in the StoreFit Tool. The individual parts of the system are described in Sections 2.5.1. onwards.

### 2.5.1 The CO2StoP Database of CO<sub>2</sub> storage locations throughout Europe

The database has been developed in Microsoft Access 2007 and a relational data structure has been implemented, thereby linking formation level data to storage units and storage units to any

The screenshot displays the CO2 STORAGE DATABASE interface. At the top, it shows the 'FORMATION' section with fields for 'FORMATION ID' (AT\_F\_20120924170441760), 'FORMATION NAME' (Hauptdolomit, tyrolian na), and 'ASSESSMENT UNIT TYPE' (Saline Aquifer with hydrocarbon fields). Below this is the 'Storage Units' section, showing 'STORAGE UNIT NAME' (Schoenkirchen SU) and 'ASSESSMENT UNIT TYPE' (Saline Aquifer with hydrocarbon fields). The 'Hydrocarbon Traps and Aquifer Daughter Units' section shows 'DAUGHTER UNIT NAME' (Schoenkirchen Uebertief) and 'ASSESSMENT UNIT TYPE' (Hydrocarbon Daughter Unit). The interface includes various input fields, dropdown menus, and buttons for adding and deleting records.

Figure 1: CO2StoP Data Entry System



associated daughter units. This has allowed for the collection of data for many storage units within a formation and many daughter units within a storage unit with a one-to-many relationship between the database tables. Unique ids have been automatically generated for each formation, storage unit and daughter unit. These unique ids have then been transferred to lower levels of data as foreign keys therefore ensuring the data is accurately linked i.e. the unique id for the formation will be automatically stored with each storage unit that is created and this will ensure data linkages and integrity are maintained.

The database is part of the overall CO2StoP Data Analysis system and has two main functions. In the first instance it has been used as the method for data collection through the implementation of a data entry system. The data entry system (see Figure 1) consists of a series of custom built tables and forms designed to guide the user through the entry of the complex data required for the project. The system allows the units of assessment to be characterised in terms of their storage resource, geological risk and economics. For the storage resource, data fields for the maximum, most likely and minimum value of each parameter have been included such that a probabilistic estimate of resource can be made using the resulting triangular property distributions.

Secondly the CO2StoP Data Analysis/Interrogation Tool has also been built on top of this database. This system provides users with the ability to filter and analyse the data in the database and subsequently export data for use in the CO2StoP StoreFit Tool, through the use of a series of custom built forms. See Section 5.4 for further information on the functionality of the data interrogation system.

A results table has also been implemented within the database which means that any calculations and analysis that are run in the CO2StoP StoreFit Tool can be imported to the database and stored alongside the original data. Again unique id's generated in the external tool mean that the results data can be linked to the original data in the database.

## **2.5.2 The CO2StoP GIS**

The objective of the CO2StoP GIS is to produce a Geographical Information System that can incorporate the polygon locations of the CO2StoP storage formations, storage units and daughter units and allow meaningful access to the data in the CO2StoP database. The GIS also provides output in a format that can be used in the CO2StoP StoreFit Tool through the development of a custom built toolbar.

### *2.5.2.1 GIS Software*

The CO2StoP GIS has been developed using ESRI's ArcGIS 10 software and is compatible with ESRI's ArcGIS 10.1. Consideration was given, at the start of the project, to the fact that some organisations may still be running older versions of the ESRI software. However, it was decided that the additional and improved functionality provided by ArcGIS10 over that of ArcGIS 9.3.1 and the fact that we should ensure the system is future proof led us to the conclusion that ArcGIS 10 should be used for the GIS. One of the main problems with using the older ArcGIS 9.3.1 is that all customisations are done in VBA and following a decision by ESRI to phase out the use of VBA in their systems, users could quickly find themselves in a position where the CO2StoP GIS did not work if they migrate to newer version of the software due to the fact that VBA customisations will not work in Arc10.1 and future versions.

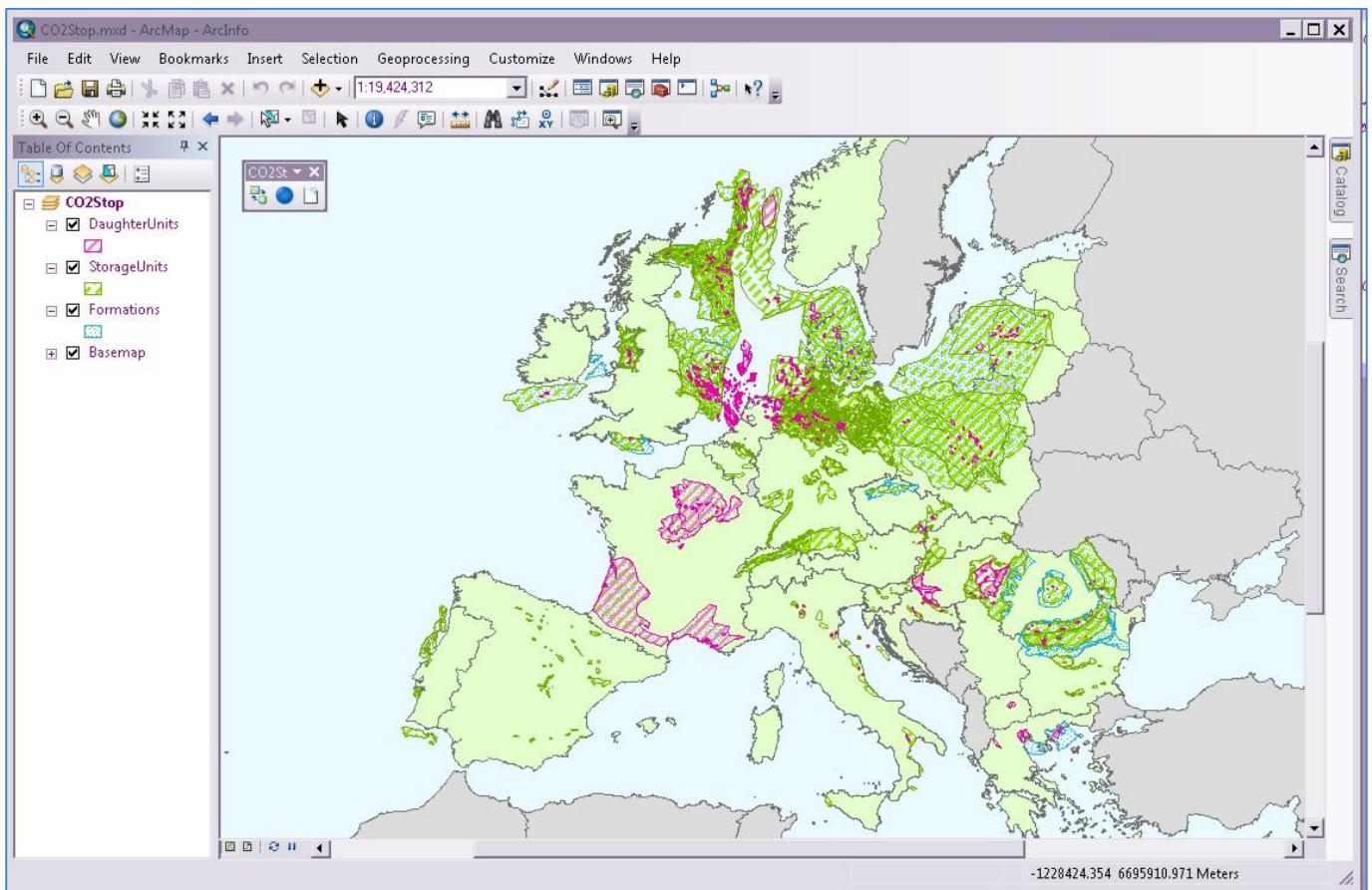


Figure 2: CO2StoP GIS

### 2.5.2.2 GIS specific data collection and collation

The primary data included in the GIS are the three-level hierarchy of geological units. They are held in the GIS as polygons that define their location and area. In descending order of size these are:

- Reservoir formations (geological formations with reservoir properties)
- Storage units (parts of reservoir formations suitable for CO<sub>2</sub> storage)
- Daughter units (hydrocarbon fields and mapped traps in aquifers)

The storage units and daughter units are the units of assessment. The units of assessment must be overlain by cap rock (= seal); a low-permeability layer of rock consisting for example of shale or halite. The reservoir formations are included with some basic attributes so that they can be displayed alongside their component storage units and daughter units. The daughter unit's layer is required because a higher CO<sub>2</sub> saturation may be achievable in traps than in the bulk of a geological formation where residual saturation trapping is the principal mechanism. Storage units and daughter units are attributed with large amounts of data which have been entered into the project database. The GIS polygons are relationally linked to the CO2StoP database, this means that as a user clicks on a formation polygon to perform any analysis they wish to carry out they will also be able to view the related data for the storage unit and the traps within that formation. The same methodology has been applied to the storage units whereby data for the associated traps are accessible when analysing the storage unit. The GIS also contains base-map data (country base-map, cities and major towns, median lines) to allow the user to locate themselves geographically.



### 2.5.2.3 CO2StoP Toolbar

A custom built tool bar has been developed for the CO2StoP GIS that provides customised tools for use in the analysis of the CO2StoP data. The toolbar includes functionality for preparing and exporting data for the CO2StoP StoreFit Tool directly from the GIS (rather than exporting from the database). This tool allows the user to select storage and or daughter units on the map and export this data in the correct format for further analysis in the CO2StoP StoreFit Tool. One advantage of using the GIS tool over using the database is that the user can see and make their selection based on location and use other data in the GIS to help with the selection process. It also allows cross border selection and export unlike the database which only allows filtering within a single country. The toolbar also provides buttons that enable easy access to both the CO2StoP Data Analysis/Interrogation tool and the copyright documentation for the project data.

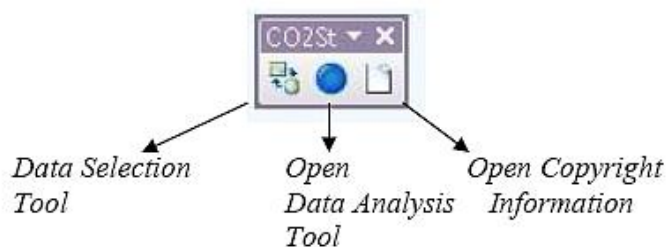


Figure 3: CO2StoP GIS Toolbar

All these tools are described in more detail in the GIS user Guide

### 2.5.2.4 Accessing the data via the GIS

The data in the database has been loaded to the GIS and a link has been set up between the polygons and the database tables based on the unique ids. This means that when clicking on a polygon using the standard ArcMap 'Identify' tool the GIS will not only display the attributes for the polygon itself but will also display any data from the database that relates to the polygon (see Figure 4). The GIS then also allows the user to 'drill' down through any subsequent data in the databases tables that is related to the polygon i.e. clicking on a formation polygon will not only allow the user to see the data for the formation but will also allow the user to see any data in the database for storage units and daughter units that lie within the formation.

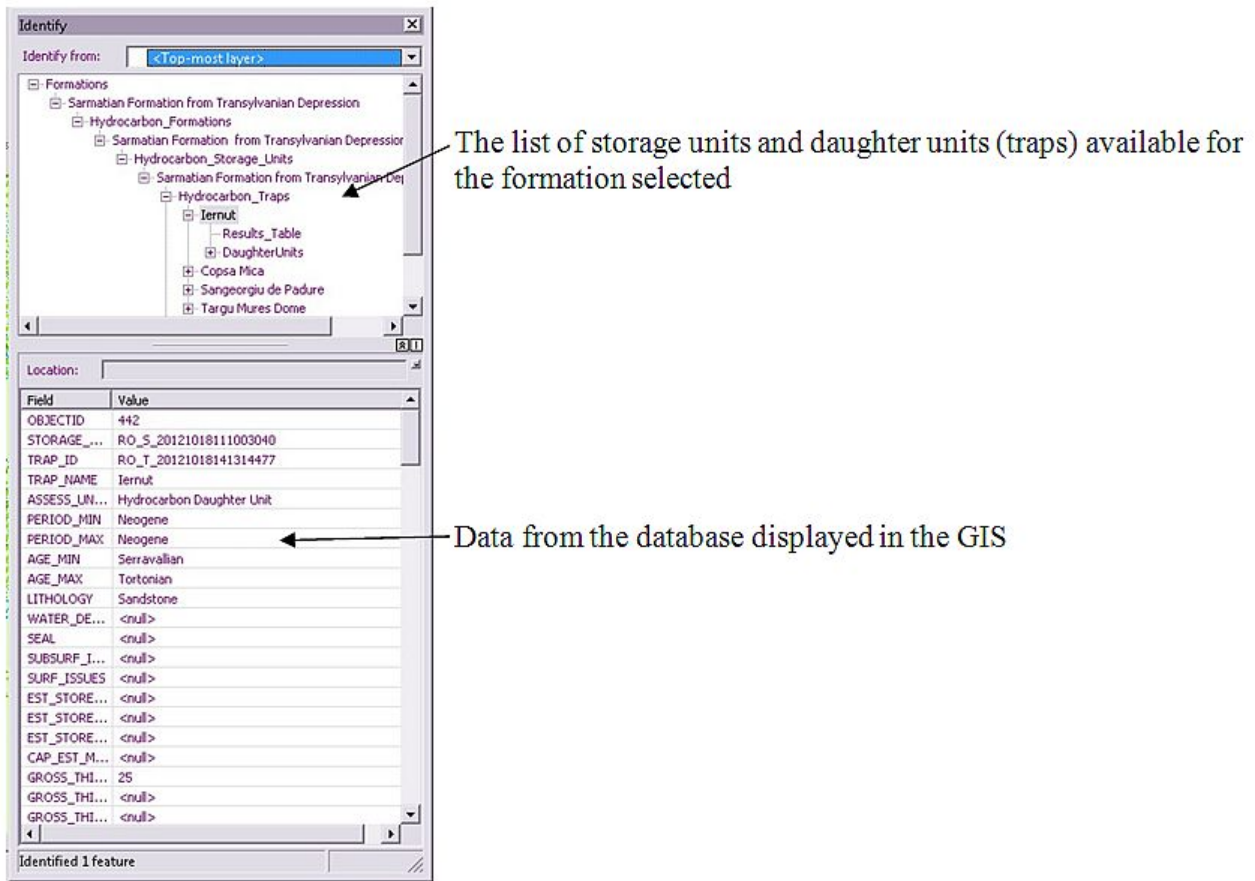


Figure 4: Viewing data in the GIS

### 2.5.3 The CO2StoP StoreFit Tool

The CO2StoP StoreFit tool provides the user with the functionality required to do more complex computations on the storage locations in the database. The tool can perform Monte Carlo simulations to produce stochastic estimates of storage capacity, using the information in the database on the stochastic character of all relevant parameters.

Built into the CO2StoP StoreFit tool are the relations given in section 3.2. The user is given full freedom to enter additional or new data, replacing or adding to the information that is in the database. To help the user to arrive at reasonable estimates, even when data density is low, default values are provided for most of the parameters involved. Examples are default geothermal gradients, hydrostatic pressure gradients. The user can also change the default relations to better suit the conditions to the selected set of storage locations.

All the data used for the computations, as well as the results, can be uploaded to the CO2StoP GIS tool, which retains these data separate

The CO2StoP StoreFit tool also provides functionality to estimate injection rates. Compared to the estimation of storage capacity, many more parameters are needed to make a reasonable estimate of injection rates. The tool provides defaults for all required data.

The CO2StoP StoreFit tool is Excel based and uses the Crystal Ball add-in tool to perform stochastic computations.





### 3 WP2: DATA SETS

#### 3.1 Data collection and collation

The methodology for collecting the data involved the distribution of the data entry system described in section 2.5.1 to all project partners so that they could enter the data for their country. Each country then returned their data to BGS and a set of stringent standardised checks were performed on each individual database (see Appendix C). These checks included, firstly, ensuring all units had a unique id and a name and, secondly, more detailed checking of the data entered to assess whether all required data was present and whether CO<sub>2</sub> storage capacity has been provided in all possible cases. Partners were then contacted for clarification and databases were returned for further work as necessary. Once all the databases had been given final approval they were then merged into a single project wide database for use in the data interrogation / CO<sub>2</sub> Storage Fitness Tool and the GIS.

The original intention was that the oil and gas field's data from the EU GeoCapacity project would be transferred straight from the EU GeoCapacity database into the CO2StoP project database by BGS. However, following the development of the CO2StoP database it became apparent that it would be too difficult to try and do this as the data structure between the 2 databases was very different and there CO2StoP database included a relational structure whereas the EU GeoCapacity database did not. It was therefore agreed with the partners affected that they would manually input their data into the new CO2StoP database. This had the added benefit of increased assurance that no confidential data was added by mistake.

#### 3.2 Database Tables and Attributes

There are three main tables in the database; these being Formations, Storage Units and Daughter Units tables (see Figure 5). The Formations table contains some very basic information on the

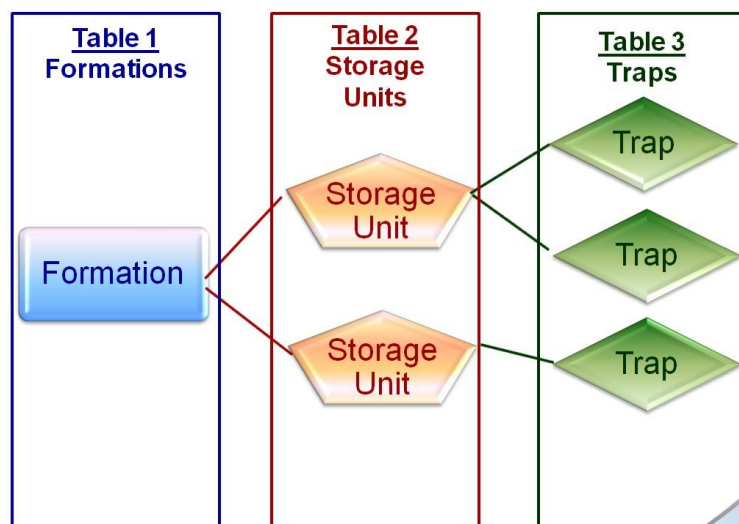


Figure 5: Database structure



formation including the location, stratigraphy and geological age of the formation. The storage units and daughter units' tables then hold the detailed technical data required to analysis the unit for CO<sub>2</sub> storage capacity and feasibility.

A general overview of the content of the database is included below. Detailed information on the database attributes is contained in Appendix B

### **3.2.1 Basic data stored for all units of assessment:**

- Assessment unit type (saline aquifer, hydrocarbon field, (i.e. formation units, storage units, hydrocarbon traps and aquifer daughter units where applicable))
- Stratigraphy (separate fields for Group, Formation, Member, Bed)
- Predominant lithology (e.g. sandstone)
- Geographic area (e.g. Southern North Sea)
- National sector if offshore (e.g. UK sector)
- Country
- Geological basin (e.g. Paris Basin)
- Name of unit (e.g. Bunter Sandstone Zone 1)
- Onshore/offshore
- Water depth (if applicable)
- Seal (name of primary seal for the unit of assessment)

### **3.2.2 Data included to estimate pore volume in saline aquifers:**

- Area
- Average thickness
- Average areal net sand
- Average vertical net:gross
- Average porosity

### **3.2.3 Data included to estimate the CO<sub>2</sub> storage resource in each unit of assessment**

Data fields have been provided in the database that enable the calculation of the Technically Accessible CO<sub>2</sub> Storage Resource (TASR) see Section 1.5 above. The additional data fields required, over and above those required to calculate the pore volume are: Storage efficiency factor (to be entered manually by the assessor or the user on the basis of their experience or published data e.g. [http://www.netl.doe.gov/technologies/carbon\\_seq/refshelf/atlasIV/](http://www.netl.doe.gov/technologies/carbon_seq/refshelf/atlasIV/)) and CO<sub>2</sub> density (to be entered manually by the assessor or user and calculated from the formation temperature and pressure).

Additional data fields required to calculate the storage capacity assuming that pressure management will not be used (see Section 1.5 above) are: compressibility factors for formation fluid and rock, and the storage pressure (from which the final storage density can be calculated). At this stage in the investigation of European storage potential it is recommended that storage is assumed to be allowed up to a level that allows a significant safety margin below the estimated leak-off pressure of the assessment unit. The recommended limiting criterion is a pressure increase of 20% above the initial reservoir pressure. This assumption is based on a summary of leak-off pressure data for the southern



North Sea given in Noy et al. (2013). This criterion could be changed if it proves to be less than optimal. CO<sub>2</sub> density is estimated at the limiting pressure and initial temperature of the reservoir.

Additional data fields required to calculate the storage capacity in hydrocarbon field daughter units (see section 1.5 above) are shown on the hydrocarbon fields tab in the database.

### 3.2.4 Geological risk data

In some cases risk data for saline aquifers will need to be evaluated on a scale. Definitions are provided to allow the assessor to determine which step on the scale each assessment unit should be allocated to. Data fields for entry of the following categories of risk data are provided:

- Primary Seal name
- Does primary seal directly overlie assessment unit?
- Estimate of primary seal chemical reactivity in the presence of CO<sub>2</sub> and water
- Minimum primary seal thickness
- Estimated capillary entry pressure of CO<sub>2</sub> in primary seal
- Secondary and other seal names
- Fault density in seal
- Fault throw relative to seal thickness
- Vertical extent of faults through overburden
- Risk of lateral migration out of unit of assessment
- Average dip of unit of assessment
- Density of existing wells penetrating the storage unit
- Well vintage
- Susceptibility of reservoir to formation damage in the presence of CO<sub>2</sub>
- Mineralogy of reservoir
- Vertical stratigraphic compartmentalisation
- Horizontal stratigraphic compartmentalisation
- Fault compartmentalisation
- Risk of adverse diagenesis

These data should be considered sufficient to allow risk scores to be assigned to the individual units of assessment. This allows the storage resource at various levels of risk to be estimated.

## 3.3 Polygon data

The polygons have very limited attributes as the main data is held in the CO2StoP database. The most important attribute in the polygons is the unique id reference from the database for the formation, storage unit or daughter unit the polygon represents. This is present to allow the linking of the polygon in the GIS to the correct data in the database. The polygons also contain a 'Remarks' attribute. This has been used to declare if the polygon is arbitrary and does not represent the actual extent of the storage or daughter unit. Information on the unit name and country are also held in the polygon purely for reference purposes. Some formation extent polygons are not available due to lack of data and therefore are not included in the 'Formations' polygon dataset. It was deemed unnecessary to ask partners to provide arbitrary formation polygons as they are not crucial to the assessment of storage potential.



### **3.3.1 Arbitrary polygons**

To allow the data in the database to be accessible via the GIS it was essential that each storage unit and daughter unit had a polygon in the GIS. Unfortunately in some cases this was difficult, either due to lack of knowledge of the extent of the unit or indeed confidentiality of the precise extent of the unit. In these cases the partners have provided arbitrary polygons which, whilst they don't represent the true area of a unit, do give the approximate location and allow for the data from the database to be fully linked into the GIS. In the case of formations where the extent could not be provided it was decided not to use this approach as the formations do not contain very much data in the database.

## **3.4 Limitations on the data sets entered into the database and provided to the JRC**

There are three main limitations on the data sets provided to the JRC:

1. The required data is not always (a) available and (b) in the public domain for any given assessment unit.
2. Parts of various jurisdictions are not considered suitable for CO<sub>2</sub> storage at present, for a variety of legal and political/social reasons. Data has not usually been provided for these regions. For example, the data from the Norwegian continental shelf are based on the Norwegian CO<sub>2</sub> Storage Atlas (Halland et al., 2011). NPD storage capacity results will be released to the CO2StoP EU database, however, the calculations for the Norwegian continental shelf are based on a different (NPD) methodology.
3. Insufficient budget was available in the CO2Stop project to allow all the data in some countries to be entered. The CO2StoP project was a service contract project on building a CO<sub>2</sub> storage potential database for aquifers and hydrocarbon fields and, as such, the budget did not allow new research to create new data but was building mainly on existing available data.



#### 4 SUMMARY BY COUNTRY OF DATA ENTERED

**Table 1** shows in which countries sufficient data has been entered to calculate each type of CO<sub>2</sub> storage resource estimate. Comments like ‘Mean only’ indicate that rather than a range (min, mean, max), only a mean value is entered into the database.

Country	TASR	Resource assuming no pressure management	Resource in structural/stratigraphical traps	
			Saline aquifers	Hydrocarbon fields
Albania	-----	-----	-----	-----
Austria	X	X	N/A	X
Belgium	Mean only	Mean Only	Mean only	N/A
Bosnia and Herzegovina	-----	-----	-----	-----
Bulgaria	Yes	X	N/A	X
Croatia	Mean only	Some mean values	N/A	X
Czech Republic	Yes	All except 2 units		
Denmark	Yes	Yes	Yes	N/A
France	X	X	X	X
Germany	X	X	X	X
Greece	Yes	Yes	Yes	Yes
Hungary	Some mean values	X	Mean only	Mean only
Ireland	Yes	Mean only	Yes	X
Italy	Yes	Only 1 unit	Yes	Yes
Latvia	Yes	Yes	Yes	N/A
Lithuania	Yes	Yes	Yes	Yes
Macedonia (FYROM)	Yes	Yes	Yes	N/A
Netherlands	X	X	X	Yes
Norway	N/A	N/A	N/A	N/A
Poland	Yes	Yes	Yes	N/A
Portugal	X	X	N/A	N/A
Romania	Mean only	Mean only	N/A	x
Serbia	X	X	N/A	N/A
Slovakia	Yes	Yes	N/A	Yes
Slovenia	Mean only	X	N/A	N/A
Spain	Mean only	Mean only	N/A	N/A
Switzerland	Yes	Yes	N/A	N/A
UK	Yes	Yes	X	Yes

TASR = Technically Accessible CO<sub>2</sub> Storage Resource.

Yes = the data is available for recalculating the storage,

X = there is not enough data to recalculate (see section 4.1 for additional information on what storage capacity data is available)

N/A = not applicable i.e. the country has not provided this type of data

Mean TASR value, see Figure 8



## 4.1 Notes

**Austria** – Although they have not entered enough data to allow the database to recalculate the storage capacity for the storage or daughter units they have entered their own estimations of storage capacity for most units.

**Bulgaria** – Although they have not entered enough data to allow the database to recalculate the storage capacity for the hydrocarbon daughter unit they have entered their own estimation of storage capacity.

**Croatia** - Although they have not entered enough data to allow the database to recalculate the storage capacity for hydrocarbon daughter units they have entered their own mean estimations of storage capacity for most units

**Estonia** – Estonia does not have the potential to store CO<sub>2</sub> however they carried out the work for Latvia

**France** – Although they have not entered enough data to allow the database to recalculate the storage capacity for the storage or daughter units they have entered their own estimations of storage capacity for most units

**Germany** – No storage unit estimations of capacity are given in the database. Although they have not entered enough data to allow the database to recalculate the storage capacity in the daughter units they have entered their own estimations of storage capacity for all units

**Greece** – Data is available to recalculate some storage capacities

**Ireland** - Although they have not entered enough data to allow the database to recalculate the storage capacity for the hydrocarbon daughter units they have entered their own estimations of storage capacity for this unit

**Netherlands** – No storage unit estimations of capacity are given in the database. Although they have not entered enough data to allow the database to recalculate the storage capacity of the aquifer daughter units they have entered their own estimations of storage capacity for all units. Most of the hydrocarbon daughter units have the required data for recalculation of storage capacity

**Portugal** – Although they have not entered enough data to allow the database to recalculate the storage capacity of the storage units they have entered their own estimations of storage capacity for all units. No Daughter units have been entered for Portugal

**Norway** – Recalculation of the Norwegian storage estimates is not allowed under the terms of this project

**Romania** – No aquifer daughter units are entered for Romania

**Serbia** - No storage unit estimations of capacity are given in the database. There are no daughter units entered for Serbia

**Slovakia** – There are no aquifer daughter units for Slovakia

**Slovenia** – There are no daughter units entered for Slovenia

**Spain** – There are no daughter units entered for Spain

**Switzerland** – There are no daughter units entered for Switzerland

**UK** – There are no aquifer daughter units entered for the UK at present, due to lack of time.



## 5 WP3: DEVELOPMENT OF FORMULAE

### 5.1 Introduction

There is an understandable reluctance in various countries to publish estimates of storage capacity in those parts of their jurisdiction in which CO<sub>2</sub> storage is not acceptable. Data will not be provided for most, and probably all, such regions.

Further work can be undertaken on the recalculation of storage capacities, based on what has been delivered within the project.

On one hand, at least one participant does not want their storage capacity estimates recalculated and will not be supplying the data that would enable this. Further actions could include discussions between the EU and/or JRC with the respective participant with a view to releasing underlying data and allowing the re-calculation of storage capacities.<sup>3</sup> On the other hand, the deliverables of the project include a database of the geological parameters necessary to make estimates of storage capacity and a set of formulae that enables subsequent calculations to be made. The JRC is thus in a position to make any estimates it wishes and, for example, could apply any storage efficiency factors it considers appropriate to any or all of the various assessment units. This would avoid any potential disagreements about storage efficiency factors used in existing assessments.

### 5.2 Storage capacity

The approach taken in the CO2StoP database is twofold:

- To use a uniform method to compute storage capacity<sup>4</sup>. MS were asked to provide storage capacity derived using the formulae described in the following sections (see 5.4.1). This enables the user of the database to compare storage capacity estimates across Europe.
- To enable the user to estimate the storage capacity using a different method. To this end, the data underlying a storage capacity estimation, such as pore volume, are also stored in the database.

The method(s) of deriving or estimating storage capacity are explained in the following sections. The methods used in the EU GeoCapacity project are used as a starting point and extended where needed. The methodology used for storage capacity estimates for hydrocarbon fields are described in section 5.2.1 (hydrocarbon fields). The capacity of saline formations is described in section 5.2.2. A model for more precise and detailed capacity estimates in oil fields including EOR is described.

#### 5.2.1 Hydrocarbon fields

For hydrocarbon fields, the method proposed here is the same as that used to obtain the storage capacity estimates that are in the EU GeoCapacity database. The only difference between the database entries in the new database and those in the EU GeoCapacity database is a possible update of the storage capacities with new data.

Below, two methods for estimating the CO<sub>2</sub> storage capacity for hydrocarbon fields are given. A database attribute is defined that identifies the methods used for each capacity estimate. Comments regarding the assumptions used for the different parameters in the methods can be entered in the 'comments' attribute in the database.

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<sup>3</sup> This action falls outside the current project.

<sup>4</sup> Norwegian capacity is based on the Norwegian CO<sub>2</sub> Storage Atlas (Halland et al., 2011). See also 4.1.



### 5.2.1.1 CSLF method for hydrocarbon field storage capacity (Method 1)

The calculation of CO<sub>2</sub> storage capacity in hydrocarbon fields uses the methodology described by Bachu et al. (2007):

$$M_{CO_2} = \rho_{CO_2r} R_f (1-F_{ig}) OGIP B_g$$

for gas fields, and

$$M_{CO_2} = \rho_{CO_2r} (R_f OOIP B_o - V_{iw} + V_{pw})$$

for oil fields. The parameters in these expressions are:

- $M_{CO_2}$ : hydrocarbon field storage capacity
- $\rho_{CO_2r}$ : CO<sub>2</sub> 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  $\ll 1$
- 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

### 5.2.1.2 Alternative method for hydrocarbon field storage capacity (Method 2)

An alternative formulation can be used, in cases where not all of the above parameters are available (Schuppers et al., 2003):

$$M_{CO_2} = \rho_{CO_2r} UR_p B$$

where:

- $M_{CO_2}$ : hydrocarbon field storage capacity
- $\rho_{CO_2r}$ : CO<sub>2</sub> density at reservoir conditions (best estimate)
- $UR_p$ : proven ultimate recoverable oil or gas
- $B$ : oil or gas formation volume factor

In this last expression,  $UR_p$  in fact represents  $R_f OGIP$  and  $R_f OOIP$ , 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.

In the EU GeoCapacity database, a minimum, maximum and expected ultimate recoverable oil or gas have been provided by each country for their hydrocarbon fields, where ultimate recoverable oil or gas is based on the sum of produced volumes and expected reserves.

For Denmark expected ultimate recoverable oil and gas is given field by field as the sum of produced volumes and expected reserves as published by the Danish Energy Authorities in yearly





reports. In some other 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 to be used.

For each country a minimum and maximum ultimate recoverable oil and gas has been calculated and for Denmark the same distribution as calculated for the Norwegian sector was used. For other countries and/or regions different distributions/calculations have been used 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 ultimate recoverable oil and gas. For Denmark, however, proven ultimate recoverable oil and gas is given as the sum of produced volumes and the low estimate for reserves for each field as published by the Danish Energy Authorities.

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 should vary with depth as a function of pressure and temperature. Likewise should the CO<sub>2</sub> density also vary 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 CSLF. To reach effective storage capacity CSLF introduce a number of capacity coefficients representing mobility, buoyancy, heterogeneity, water saturation and aquifer strength, respectively and all reducing the storage capacity. However, there are very few studies and methodologies for estimating the values of these capacity coefficients and hence we have chosen not to distinguish between theoretical and effective storage capacity for hydrocarbon fields.

### **5.2.2 Saline formations**

Several methods are proposed to obtain a storage capacity estimate method for saline formations. The method used can be chosen depending on the level of knowledge and available data on a given structure. All methods described below assume that storage capacity is created by increasing the pressure in the saline formation. This compresses the fluid(s) and the rock. Due to the limited compressibility of fluids and rock, significant volumes of saline formation are required to create useful storage capacities. Additional storage capacity can be created by producing brine from the saline formation, i.e., by extracting brine via wells. This is discussed further in section 5.2.2.6 .

As in the case of hydrocarbon fields, a database attribute defines the method that was used to obtain the storage capacity estimate. A 'comments' attribute is available to list any additional assumptions used.

The method available for estimating the storage capacity of saline formations is:

1. Formation pore volume, storage efficiency coefficient. When only limited knowledge is available on a potential storage volume, the storage capacity can be estimated from the bulk volume of saline formation, multiplied by an average porosity and by a storage efficiency factor. The bulk formation volume is the volume that is hydraulically connected. Section 5.2.2.1 discusses this method.



2. Pore volume, pressure increase, compressibility. When information is available to estimate the pressure increase that can be applied to the hydraulically connected volume, this method provides a more reliable estimate of the storage capacity. ). See section 5.2.2.2 .
3. As 1 or 2, limited by the volume of trap(s). Storage capacity can be limited by the connected volume that accommodates the pressure increase, or by the traps that contain the buoyant CO<sub>2</sub>. If the volume of the traps is included in the storage capacity estimated, this method is used. See section 5.2.2.3 .
4. Capacity from detailed study (site characterization study). The most accurate storage capacity estimate is obtained after a detailed site characterization study. In such a study, all available data is collected, a detailed geological model of the connected volume is created and a reservoir engineering study is performed to obtain a realistic storage (and injection) capacity estimate. See section 5.2.2.4 .

#### 5.2.2.1 Connected pore volume and storage efficiency (Method 1)

The approach used in EU GeoCapacity for storage capacity estimation in deep saline aquifers is a slightly simplified and/or modified version of the method presented in Bachu et al. (2007). Bachu et al. (2007) define both theoretical and effective storage capacity for a basin or region 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<sub>2</sub> 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.

For simplification we would like to define the term storage efficiency in this report as the ratio of used space over available space. Furthermore we would like to introduce effective regional storage capacity estimates based on bulk volume of aquifers and applying a different storage efficiency factor as a supplement to regional estimates based on the sum of capacity in individual identified traps.

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 hence do not include 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. We thus propose to apply a storage efficiency factor applicable to the bulk volume of the aquifer:

$$M_{CO2b} = A h NG \phi \rho_{CO2r} S_{eff}$$

where:

- $M_{CO2b}$ : regional “bulk” storage capacity
- $A$ : area of regional aquifer
- $h$ : average height of regional aquifer
- $NG$ : average net to gross ratio of regional aquifer



- $\phi$ : average reservoir porosity of regional aquifer (best estimate)  
 $\rho_{CO_2r}$ : CO<sub>2</sub> density at reservoir conditions  
 $S_{eff}$ : storage efficiency factor (for bulk volume of regional aquifer)

In the above expression, the product  $AhNG\phi$  is the total connected pore volume. For bulk volumes of regional aquifers it is suggested to use a storage efficiency factor of 2 % based on work by the US DOE. Frailey (2007) used Monte Carlo simulations to find a P50 of storage efficiencies between 1,8 and 2,2% of the bulk volume of a regional aquifer (with low and high values of 1 % and 4 %, respectively). The work included Monte Carlo simulations of the distribution of values for a number of terms defining the pore volume of regional aquifer and a number of terms reflecting local formation effects in the injection area of a specific injection well.

Bachu et al. (2007) 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 on the local geological variations and is not necessarily neither 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 few observations. If limited information is available instead suggest that a default value of 0.25 is suggested. 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<sub>2</sub> 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 a default value of 650 kg/m<sup>3</sup> is suggested.

As a regional estimate based on bulk volume of an aquifer and not on trap volumes 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<sub>2</sub> 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.

#### 5.2.2.2 *Connected pore volume and pressure increase (Method 2)*

A more reliable estimate of the storage capacity of a saline formation can be obtained, when the level of knowledge allows an estimate of the allowable pressure increase to be made. Combined with the compressibility of the fluids and rock, the storage capacity estimate is derived from (see, e.g., US DOE. Frailey (2007)

$$M_{CO_2b} = A h NG \phi \rho_{CO_2r} \Delta p (\beta_r + \beta_f)$$

where, in addition to the parameters defined above:

- $\Delta p$ : the pressures increase (relative to the initial pressure)  
 $\beta_r$  the compressibility of the matrix  
 $\beta_f$  compressibility of the fluid

#### 5.2.2.3 *Capacity estimate, limited by volume of trap(s) (Method 3)*

If the knowledge and level of detail exists and are available a regional capacity estimates that is more reliable than those obtained with either method 1 or method 2 is to provide storage capacity



estimates that take into account the volume in traps, where the buoyant CO<sub>2</sub> can be safely retained. It should be emphasized here that storage capacity in saline formations is not only limited by the pressure increase that can be sustained by the formation and the allowable pressure increase, but also by the traps that where CO<sub>2</sub> collects after injection. In a high-level regional screening study, proving the existence of suitable traps and the location of injection sites may be deferred to a later and more detailed subsurface characterization (see, e.g., Neele et al., 2011). The volume of CO<sub>2</sub> that is derived from the connected volume and assumed pressure increase must nevertheless be stored in a structure that will retain the CO<sub>2</sub>. Figure 6 shows the concept. The blue area, confined by impermeable faults (as shown) or bounded by pinching out of the formation, defines the total connected pore volume. The pressure in this volume can be increased to create space for CO<sub>2</sub> (illustrated by the red volume in the Figure 6). The volume of CO<sub>2</sub> that can be trapped is defined by the volume in the traps. The smaller of these two volumes (CO<sub>2</sub> volume from pressure increase, trap volume) defines the total storage volume.

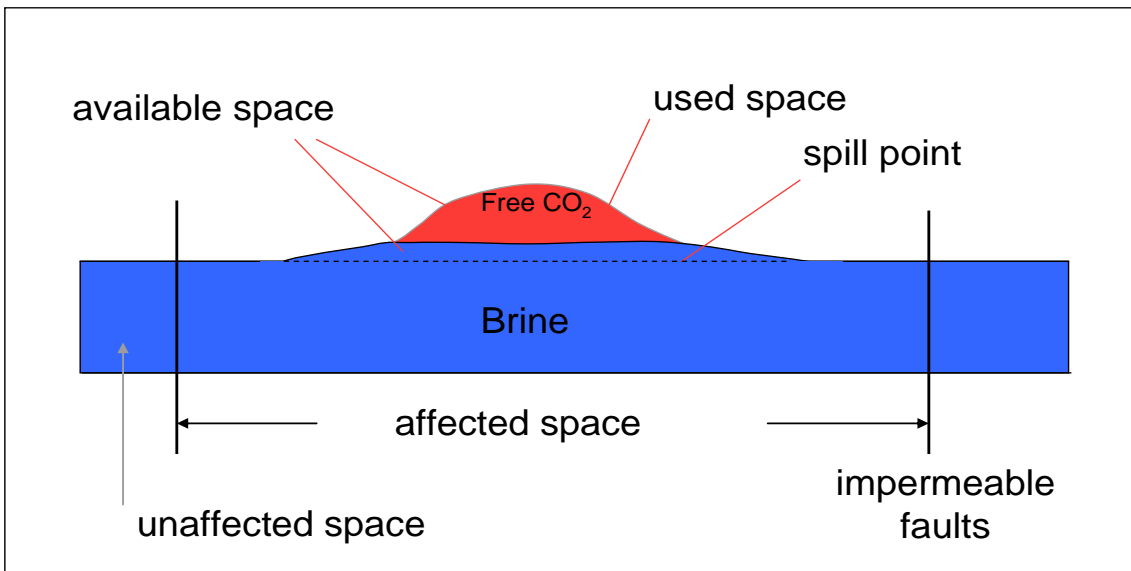


Figure 6: A schematic picture of a CO<sub>2</sub> storage site.

#### 5.2.2.4 Capacity estimate from detailed site characterisation study (Method 4)

A site characterisation study is one of the elements required for a storage licence application. In such a study all available data on the storage formation is collected to model the static and dynamic<sup>5</sup> behaviour of the formation. One of the results of such a study is the storage capacity. This estimate is based on all available data and on detailed modelling of the dynamic behaviour of the storage formation.

#### 5.2.2.5 Capacity estimate from injection tests (Method 5)

The most reliable storage capacity estimate is obtained from an injection test, or from a prolonged injection period. A test injection will demonstrate not only the feasible injection rates, but, when the injection is continued for a sufficiently long time, will also show the size of the connected volume. An injection test is one of the last activities, prior to starting an injection and storage project.

<sup>5</sup> The rate at which CO<sub>2</sub> can be injected into a reservoir rock



#### 5.2.2.6 *Storage capacity increase through production of formation fluids*

Storage capacity in saline formations can also be created by producing the in situ fluids, i.e., by pumping out the formation water. Although this method has the advantage of potentially creating large storage capacity, current regulations do not easily allow this approach to be followed.

In the database storage capacity estimates, production of formation fluids to create storage capacity is assumed not to be feasible. In the Database Analysis/Interrogation Tool, the user can use various levels of the storage efficiency factor to take formation fluid production into account.

### **5.3 Injection rates**

Injection rates are an essential element of feasibility assessment of storing CO<sub>2</sub> at a site. Injection rates depend on a large number of parameters, some of which can be obtained only through drilling. These parameters include those describing the geology (such as permeability, depth, formation thickness, number of wells), and those describing the transport and injection system (such as well and tubing, wellhead pressure).

The approach taken with the database is to provide the functionality in the database (in the Database analysis/Interrogation Tool), to be able to estimate injection rates when the required data become available, using a number of default values for data that depend on the physics of the transport system.

When injection rates are available for a given site from a detailed site characterisation study, these rates can be entered into the database. Database attributes are available that define an injection rate plateau (in Mt/yr) and the duration of the plateau (years).

The reservoir related information required to estimate injection rates is reservoir permeability. Other data needed for the estimation of injection rates are already present in the database. These include, among others, depth, formation thickness, pressure, temperature.

### **5.4 CO2StoP Data Analysis/Interrogation Tool**

#### **5.4.1 Introduction**

The Data Analysis/Interrogation Tool is a combination of Microsoft Access (Data Interrogation tool) and Excel (StoreFit tool) with external code (linked to Excel) to perform injection rate calculations. Calculations that can be done with the Database Analysis/Interrogation Tool include:

- Storage capacity (see section 3);
- Injection rates (see section 5.4.3);
- Stochastic analyses of the storage capacity and injection rates (see section 5.4.4).

Additional functionality is also provided by ArcGIS outside of the tool itself allowing users to view, analyse and prepare data for the StoreFit tool.

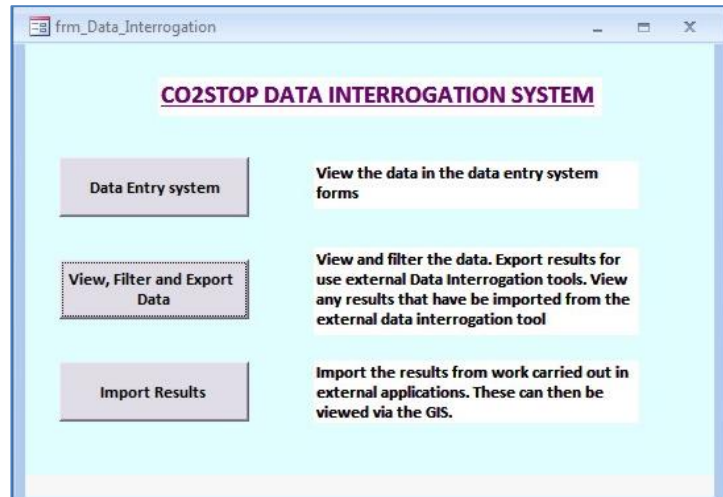


Figure 7: CO2StoP Data Interrogation System

The functions of the different elements of the tool are described below:

1. Microsoft Access. The database itself is a Microsoft Access relational database on top of which has been built the customised forms required for the data interrogation system (see Figure 7).

All the standard filtering and data selection functionality of Access is available to the user should they wish to use it. Functionality to perform simple calculations, such as those related to storage capacity, can be done within Access and have been implemented on the data entry forms (see Figure 8). The attributes in the database are sufficiently extensive to allow categorisation of sites with respect to measures of confidence or risk. Properties such as reservoir quality, available data, and presence of well data can be used as selection criteria. Useful categorisations were proposed and used in the Norwegian Storage Atlas (Halland *et al.*, 2011); similar categories are defined in the interrogation tool

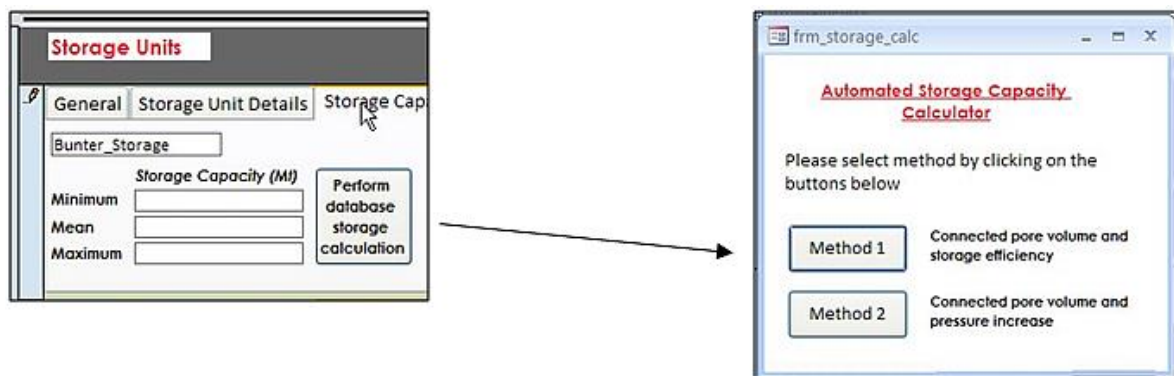


Figure 8: Storage Capacity Calculations in the CO2StoP database

A custom built form has also been implemented in the database that will allow the user to filter, select and export data that they wish to use in the excel based tool (see Figure 9).

A simple tool has also been developed to allow the user to import any results of further analysis in the Excel based tool. These results are stored in the Results table within the database so that the primary data is not modified. This data is then linked into the polygons within ArcGIS.



2. ArcGIS. A link between Access and ArcGIS allows the geographical visualisation of the data within the database through links to polygons representing the storage locations, ArcGIS can then be used as main filtering and selection platform if the user prefers this to using the CO2StoP Database Analysis/Interrogation Tool. The link between the database and GIS allows the user to interrogate the different levels of data held within the database (formation level, storage unit level and daughter unit level) and perform on screen selections of the data with the ability to view the results in the database tables. Standard ArcGIS tools can also be used to filter and analyse the data based on the extensive attributes in the database table and the results can be seen both on-screen and within the attribute table. A custom built tool also guides the user through selecting data for use in the CO2StoP StoreFit Tool and the GIS will export the data in the format required for further analysis in the tool. Pre-defined categories are provided; examples include reservoir quality and data availability, showing the site properties in a colour code (such as green – yellow – red).

Figure 9: Filtering data in the Database Analysis/Interrogation Tool





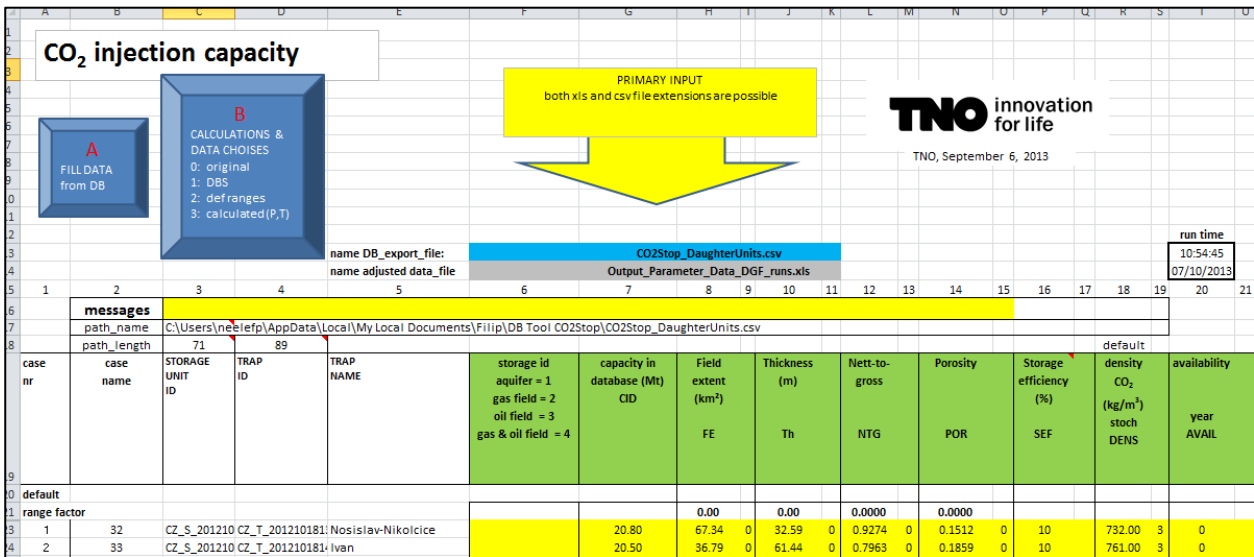


Figure 11: Screenshot of the StoreFit Tool that allows the user to re-compute storage capacity taking into account the uncertainties in the data entered in the database.

### 5.4.3 Injection rates

The algorithms used to estimate injection rates are taken from the TNO Carbon Capture & Storage Techno-Economic Model. This is an integrated well / reservoir injection and cashflow model which provides output on a number of key performance indicators, such as the unit technical costs and the break even CO<sub>2</sub> price at the well head. Figure 12 shows a screenshot of the injection rate part of the StoreFit Tool.

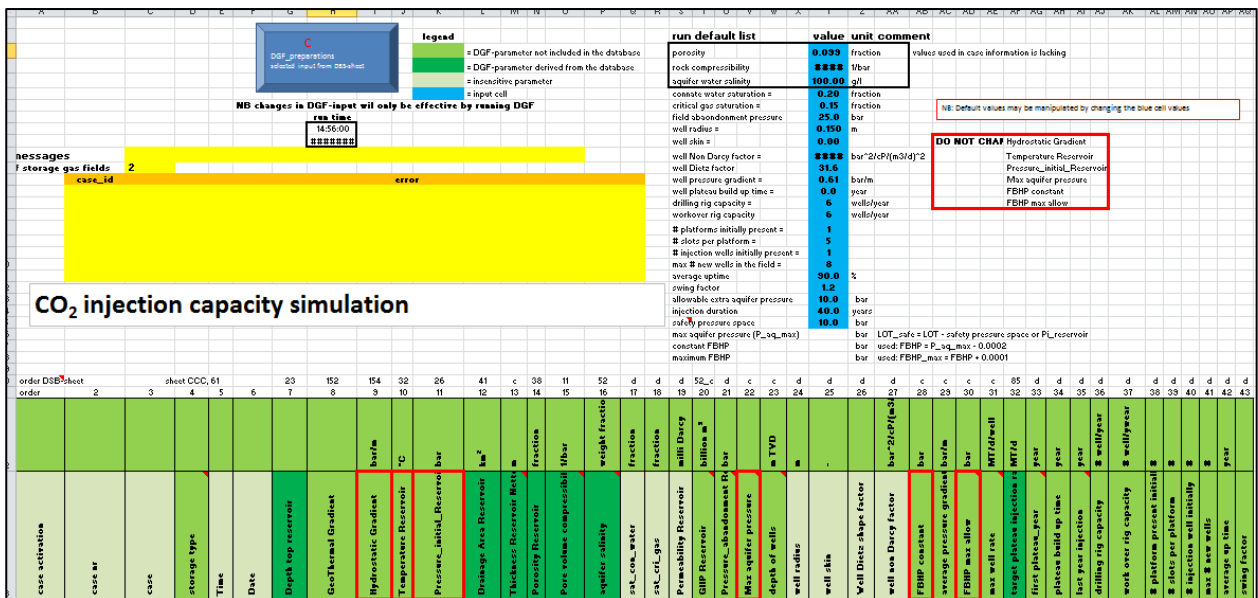


Figure 12: Screenshot of the StoreFit Tool, this time showing the screen that allows the user to review and define data for the estimation of injection rates.



The model consists of two interconnected sections:

- the reservoir model, determining the CO<sub>2</sub> rates into the reservoir and the corresponding pressure build-up in the reservoir;
- the well model, determining the pressure and temperature distribution in the well;

These are described in some detail below.

#### 5.4.3.1 Reservoir model

The reservoir is modelled as a single system, without compartments, with one average reservoir pressure and a constant temperature. The reservoir is assumed to behave like a tank, which is gradually filled with CO<sub>2</sub>. The model uses a semi-steady-state inflow equation, for a variable number of injection wells. The pressure build-up over time is determined by the realized CO<sub>2</sub> injection rates over time, using a material balance to compute pressure in the reservoir. The pressure-dependent CO<sub>2</sub> density is taken into account. The time step in the model is 1 year.

Injection of CO<sub>2</sub> is only possible when the flowing bottom hole pressure (FBHP) in the well(s) exceed the average reservoir pressure. The larger the difference between FBHP and mean reservoir pressure, the higher the injection rate. The relation between the pressure difference and the injection rate is non-linear and is modelled using a quadratic equation. The linear term in this equation, i.e. the first order relation between injection rate and pressure difference<sup>6</sup>, is the injectivity of the well and depends on the product of reservoir thickness and permeability, the CO<sub>2</sub> viscosity, the well diameter and the reservoir size, among other factors. Well skin (a parameter representing the flow from well into reservoir) is included. The second-order (non-linear or non-Darcy) term is an important input parameter in the model: results are sensitive to variations in this parameter. However, obtaining a field-specific value is rather difficult: it can be inferred from well test results, but these data are often not available or confidential.

The model is capable of making decisions based on the situation at each time step. An example is the target injection rate. If the realized CO<sub>2</sub> injection rate falls below the target injection rate, the model checks whether the injection rate can be increased through the construction (or reworking) of platforms, by making available additional wells (existing or new), or by installing additional compression capacity. Based on user defined settings, the model also determines when injection is no longer economically feasible and abandonment should take place.

#### 5.4.3.2 Well model

The well model determines the pressure and temperature distribution in the well. The well is modelled as a vertical tube with a constant inner and outer diameter. The two most important terms in the pressure equation are the static head, which is the pressure build-up due to the weight of the CO<sub>2</sub> column in the well and the pressure loss due to viscous forces resulting from the flow of CO<sub>2</sub> through the well. Pressure changes due to acceleration are neglected. Important parameters in the equations are the (temperature and pressure dependent) CO<sub>2</sub> viscosity and density, the tubing size and roughness, the depth of the well, among other factors. Temperature changes are due to heat conduction from the reservoir to the well. Examples of model data are the heat conductivity of the well and the heat capacity of CO<sub>2</sub>. Input to the well model is also the tubing head pressure and temperature (which can be altered in reality by installing compressors, heaters, etc.). A restriction to the well model is that wells are modelled as strictly vertical. In reality, a well drilled into a field is often deviated, so that its length can be significantly higher than its true vertical depth. In this case,

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<sup>6</sup> Although the text refers to pressure, the model computes injection rates in the pseudo-pressure domain.



the model will underestimate the temperature rise in the well as well as the pressure drop due to viscous forces.

#### **5.4.4 Stochastic analyses**

Many of the attributes of the storage locations in the database include a specification of their uncertainty, in the form of minimum and maximum values. The interrogation tool allows the user to perform the computations described above stochastically, i.e., taking into account the uncertainty in the geological data. This is also possible in analysing storage capacity for a region, or as a function of time. This functionality is provided through an Excel plug-in (Crystal Ball).

The advantage of Crystal Ball is that stochastic analyses can be done quickly and easily. An alternative route would be to provide an external code that handles all uncertainties, but this requires time-consuming code development, with a functionality that is likely to be at a lower level than that offered by Crystal Ball. Crystal Ball software price is about €900.

#### **5.4.5 CO<sub>2</sub> properties**

The storage capacity and injection rate modules require the properties of CO<sub>2</sub> as one of the inputs. The database interrogation tool has the capability to compute density and viscosity of pure CO<sub>2</sub>, as a function of pressure and temperature. The algorithms used are those of Span & Wagner (1996).

A reliable estimate of storage capacity and injection rates requires the presence of a series of attributes in the database, some of which may not be known. The user is given the opportunity to input new data or his or her own estimates of the missing parameters for the storage location. The tool provides default depth profiles of density, temperature, as well as default values for other parameters that are required to perform the calculations. The user has full control over the value of the defaults.

All data used to perform the calculations, either values from the database, user supplied data or default values, can be uploaded to the central database for future reference.

#### **5.4.6 Implementation of CO2StoP Data Analysis/Interrogation Tool**

The database exists in MS Access format and the links between MS Access, Excel and ArcGIS are straightforward, allowing the user to make a selection from the database within the GIS using any of the attributes and to view the results geographically on screen. MS Access or ArcGIS can also easily export the data in the correct format for use in the CO2StoP StoreFit Tool which is built in Excel.

The calculations of storage capacity and injection rates are performed within Excel (storage capacity), or a separate, stand-alone engine (injection rates). Those results can also then be imported into the CO2StoP Database and then accessed through the location polygons on the map.

The stochastic functionality is provided for by a plug-in in Excel (Crystal Ball). Geographic visualisation of stochastic results is not straightforward and will not be implemented as a first priority.



## **6 WP4: ESTIMATES OF CO<sub>2</sub> STORAGE CAPACITY**

Estimates of storage capacity are shown in Appendix D. It should be borne in mind that these estimates are a first pass attempt to roughly quantify the CO<sub>2</sub> storage capacity of participating countries. They require further refinement and should not be regarded as definitive.

- The estimates are based on:
  - Filtering at various levels (national, regional; risk based; confidence based)
  - Filtering at storage level (saline formations, hydro carbon fields, (structural) traps versus no trap)
  - Include probabilistic information in database

## **7 WP5: PROJECT MANAGEMENT**

The general management of the CO2StoP project included planning & direction of the activities, organisation of meetings, management of budget, follow-up of progress, approval of deliverables and reporting. The CO2StoP project was managed mainly through decisions in the consortium on a number of consortium meetings. Beyond this, the work was organised by the project co-ordinator and consortium member by mail and telephone correspondence with DG Energy, JRC and the partners. The work included also to facilitate the partner's collaboration and input to the work packages, and to lead the preparation of the interim and final report. Here is the development and course the project described.

The CO2StoP project started with a consortium-planning meeting at EuroGeoSurveys office in Brussels January 10<sup>th</sup> 2012 followed by the kick off meeting, January 11<sup>th</sup> 2012 with the Commission and JRC.

The management further included preparation of the consortium contract and contracts with all subcontractors.

The consortium agreement following the DESCAs contract model was prepared in the early phase of the project, and all three partners in March 3<sup>rd</sup> 2012 signed it. A subcontractor agreement for each subcontractor was also prepared after agreement with Kai Tullius, EC: The subcontractor agreement was sent out for signing primo ultimo February 2012.

A kick-off meeting was held at GEUS with 31 participants representing 23 of the in total 29 partners (consortium and subcontractors), in March 2012. The remaining subcontractor partners were updated through a telephone or Skype conference during May 2012. At the meeting, there were presentations and discussions of the methodology to be used for CO<sub>2</sub> storage capacity estimation and risk assessment, the development of the interrogation and calculation tool, introduction to the GIS and the requirements to input data, information about deadlines and financial issues.

The interim meeting with the Commission and JRC was held in Brussels June 19<sup>th</sup> 2012. The meeting was contractually agreed to discuss the interim report that was submitted at the end of month 4, and to reflect on the work completed and to discuss next steps. The consortium presented in detail the work completed and the planned next steps. On the management side, all legal arrangements, notably the subcontracts were put in place. The interim report was approved and the general database structure as presented was deemed to be sufficient.



As foreseen, the project entered into its most risky phase in July 2012 when the partners started to enter data. It was somewhat unclear if the partners were in possession of the necessary data, and willing to supply all data and have sufficient resources to enter the data in the limited timeframe. This became only clearer once the partners have been requested to enter the data. Nicola Smith (BGS) reported that a number of partners were late in submitting data, had problems uploading data or with the format of the data and Niels Poulsen (consortium leader, GEUS) started helping to chase the missing partners. The last data arrived about 4 month too late causing a major deviation from the project plan, and two partners (AGS from Albania and UT from Bosnia-Herzegovina) were lost due bad communication (no reaction to correspondence by mail, fax or phone). See Figure 13.

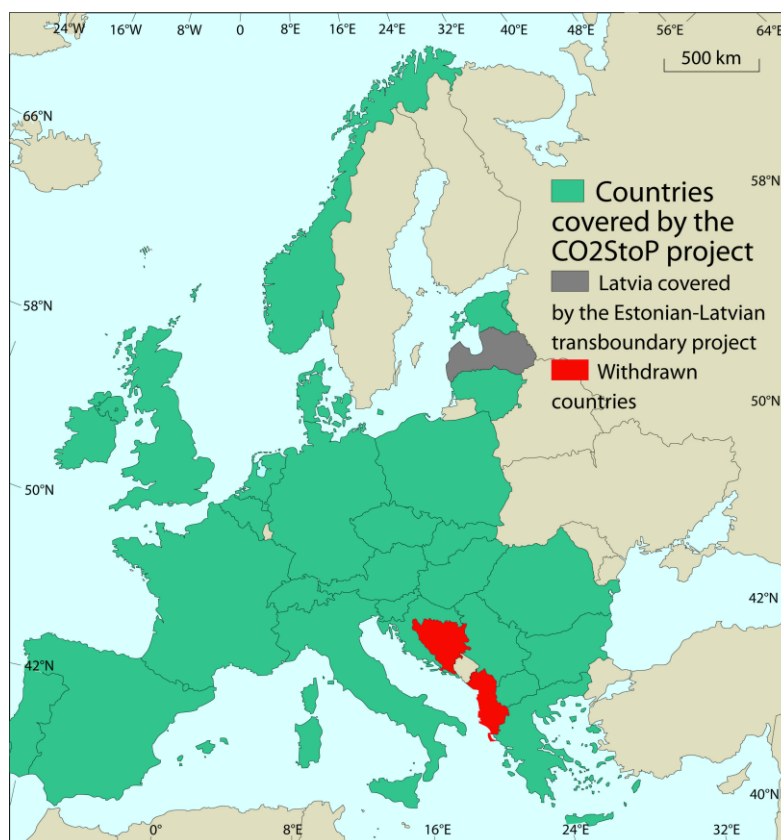


Figure 13: 27 countries were covered in the CO2StoP project. Latvia was covered by the Estonian-Latvian border project.

As agreed at the interim meeting the consortium informed the Commission about the problems or concerns with the partners and the evolution of the data entry, partly directly by phone or mail and partly via the minutes of the consortium meetings. The Commission approved the omission of the two partners from Albania and Bosnia-Herzegovina from the project.

The consortium had agreed to grant JRC access to the data interrogation system pilot at the interim meeting and when it was ready, the JRC was invited to comment on the data interrogation system pilot starting from April 23, 2013 onwards and for GIS tool from June 19, 2013 onwards. The final Database Analysis/Interrogation Tool was delivered in the end of August 2013 at the second meeting with JRC at TNO.

## 7.1 Dissemination

CO2StoP has been represented and presented at three international meetings and conferences since the start of the project. At the 7th CO2GeoNet Venice Open Forum in 2012 as a poster, and at the 5th CGS Europe Knowledge Sharing Workshop, 8th Venice Open Forum in 2013 as an oral contribution.

CO2StoP was presented as a keynote presentation entitled: “European Storage Opportunities. (Location of onshore & offshore formations suitable for CO<sub>2</sub> storage in Europe? Depleted oil & gas fields, enhanced oil/gas recovery, saline formations & coal seams. Storage capacity parameters.



What is the total current & potential CO<sub>2</sub> storage capacity in Europe?)” at the 5th Carbon Capture & Storage Conference arranged by ACI in Rotterdam, the Netherlands May 15-16th 2013

Finally, the consortium has been formed for looking into possibilities of dissemination of CO2StoP results as a publication.

## 7.2 Conclusion

The project CO2StoP started at the beginning of 2012 and finished by the end of 2013. The objective to build a CO<sub>2</sub> storage potential database for the European Commission and the Joint Research Centre (JRC) has been completed. The CO2StoP project includes 29 partners from the start; however, two partners were lost during the project.

## 7.3 Overview of the deliverables produced in the CO2StoP project:

Below is given an overview of the deliverables produced in the CO2StoP project:

### Reporting

Reports and database available on the project FTP-site:

- A Database of CO<sub>2</sub> storage locations throughout Europe,
- A Database Analysis/Interrogation Tool,
- A tool to compute storage capacities and injection rates (“StoreFit”), Poulsen, N.E., Holloway, S., Neele, F., Smith, N.A., & Kirk, K., 2012: Interim Report. CO2StoP (Assessment of CO<sub>2</sub> storage potential in Europe) European Commission Contract No ENER/C1/154-2011-SI2.611598 Report. 27 pp.
- Poulsen, N.E., Holloway, S., Neele, F., Smith, N.A., & Kirk, K., 2013: CO2StoP Final Report. CO2StoP (Assessment of CO<sub>2</sub> storage potential in Europe) European Commission Contract No ENER/C1/154-2011-SI2.611598 Report. 59 pp.
- Smith, N.S., Obdam, A., & Neele, F., 2013: CO2StoP Data Analysis System User Guide. CO2StoP (Assessment of CO<sub>2</sub> storage potential in Europe). European Commission Contract No ENER/C1/154-2011-SI2.611598 Report. 29 pp.
- Various minutes (see list consortium meeting above)

### Conference papers

- Poulsen, N.E., Holloway, S. & Neele, F. 2012: CO2StoP. Assessment of CO<sub>2</sub> storage potential in Europe Specific Targeted Research Project. 7th CO2GeoNet Open Forum. San Servolo Island, Italy. 17 April 2012. Poster
- Poulsen, N.E., Holloway, S., Kirk, K., Neele, F. & Smith, N., 2013: CO2StoP & European CO<sub>2</sub> Storage Atlas. The Venice Open Forum 2013, 5th CGS Europe Knowledge Sharing Workshop. San Servolo Island, Italy. 11 April 2011
- Poulsen, N.E., 2013: European Storage Opportunities. Location of onshore & offshore formations suitable for CO<sub>2</sub> storage in Europe? Depleted oil & gas fields, enhanced oil/gas recovery, saline formations & coal seams. Storage capacity parameters. What is the total current &



potential CO<sub>2</sub> storage capacity in Europe? The 5th Carbon Capture & Storage Conference. Active Communication International (ACI). Rotterdam, the Netherlands. May 15-16th 2013

## **Publications**

- Poulsen, N.E., 2012: The need for a CO<sub>2</sub> Geological Storage European Atlas ENeRG Position Paper September 2012. 4 pp.
- Poulsen, N.E., 2012: European CO<sub>2</sub> Geological Storage Atlas. GEO Energy, the Newsletter of the ENeRG Network, **26**: 1.
- Poulsen, N.E., 2012: ENeRG Partners Involved in the European Commission CCS database project - CO2StoP. GEO Energy, the Newsletter of the ENeRG Network, **26**: 2.
- Poulsen, N.E., 2012: EGS Partners Involved in the European Commission CCS database project - CO2StoP. EuroGeoSurveys NEWS. **8**: 14

## **In the project period the following meetings were held:**

- January 10<sup>th</sup> 2012: Consortium planning meeting in Brussels
- January 11<sup>th</sup> 2012: Kick-off meeting with EC/JRC in Brussels
- March 5<sup>th</sup> 2012: Kick-off meeting (Project Meeting) in Copenhagen at GEUS
- June 19<sup>th</sup> 2012: Interim meeting in Brussels with EC/JRC
- November 8<sup>th</sup> 2012: Consortium meeting
- November 29<sup>th</sup> 2012: Consortium meeting
- December 17<sup>th</sup> 2012: Consortium meeting
- January 11<sup>th</sup> 2013: Consortium meeting
- February 2<sup>nd</sup> 2013: Consortium meeting
- May 2<sup>nd</sup> 2013: Consortium meeting
- May 30<sup>th</sup> 2013: Consortium meeting
- June 11<sup>th</sup> 2013: Consortium meeting, with DG ENERGY, Unit C1 – Renewables and CCS Policy (Rue de Mot 24)
- August 14<sup>th</sup> 2013: Consortium meeting
- August 29<sup>th</sup> 2013: Consortium meeting,
- October 25<sup>th</sup> 2013: Consortium meeting

## **8 DISCUSSION**

### **8.1 Methodology**

The CO2StoP project builds on the preceding EU GeoCapacity project by providing a database, GIS and calculation engine capable of providing probabilistic estimates of CO<sub>2</sub> storage capacity in addition to the deterministic results obtained in EU GeoCapacity.

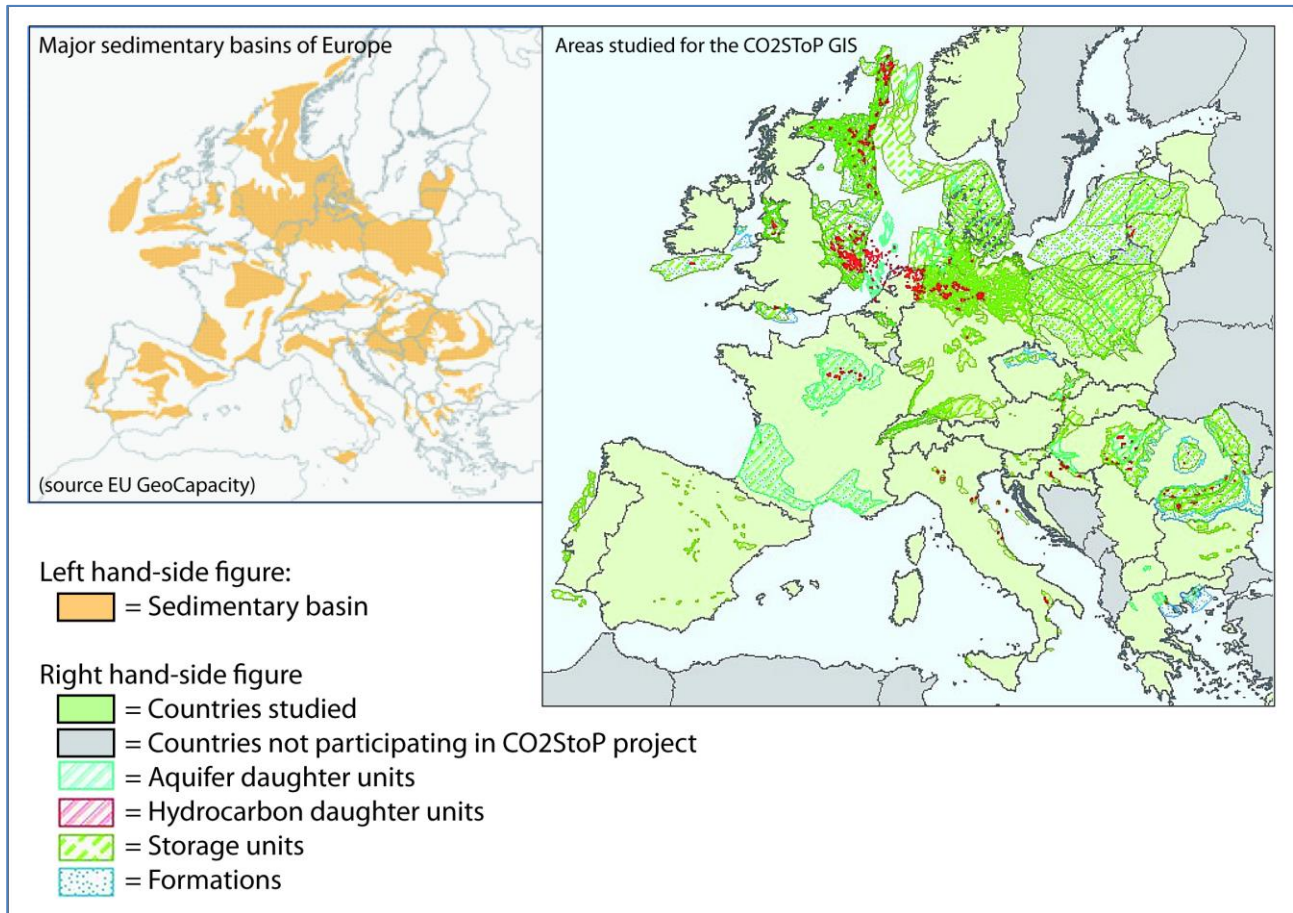


Figure 14: Comparison of major sedimentary basins of Europe (left) and reported reservoirs in CO2StoP (right).

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 EU GeoCapacity project and a CSLF Task Force has been active since. The paper “Estimation of CO<sub>2</sub> 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<sub>2</sub> storage capacity. As EU GeoCapacity did, the CO2StoP methodology complies with the CSLF recommendations. The methods and calculations of fractions of the resource, used in the CO<sub>2</sub>Stop project also accord with the recent IEA proposals for harmonising CO<sub>2</sub> storage capacity estimation methodologies (Heidug 2013). In particular, the CO2StoP methodology can calculate the TASR, the storage resource assuming pressure management will not be used and the storage resource in structural and stratigraphic traps (that latter divided into two subsets – hydrocarbon fields and aquifer daughter units).

## 8.2 Results

The assessment of the various fractions of the CO<sub>2</sub> geological storage resource performed in the CO2StoP project is currently at a provisional level only. Unfortunately, large differences exist between what kind and quality of data each country has available, and also what relevant data is in the public domain and therefore can be reported. For example, there are major differences in countries that only have data available from traps for buoyant fluids (where the TASR will be low because potential for storage outside such traps by residual saturation will not be accounted for) and





countries having included aquifer formation data (where the TASR calculation will be more meaningful). In the great majority of countries, uncertainties also remain related to lack of reservoir parameter data, acquisition of which potentially will require a sustained campaign of geological mapping and characterisation of storage capacity, or at least significantly more time and financial resources to assemble and enter all available data. These factors limit the results obtained from the CO2Stop project and it is recommended that further resources are targeted on improving the results. Both reporting and data could be improved if greater resources were made available.

In a European context, the Technically Accessible CO<sub>2</sub> Storage Resource (TASR) or theoretical storage resource should only be used for extra-European international resource comparisons because it is certain that the TASR is several times larger than the practical CO<sub>2</sub> storage capacity. Consequently quoting the TASR can be misleading to policymakers, and the press, who may not grasp the critical distinction between resource and reserve estimates.

The tables in Appendix D show a summary of the storage capacity totals based on the data available in the database (Table 2 – Table 11). These include the totals of the user entered storage capacity (calculated independently by the partner involved) plus any database calculations carried out by the user at the time of data entry. Subsequent to this some standard calculations have been carried out on the data to allow the comparison of storage capacities across the partner countries. For the Aquifers these involved calculating the capacity using the storage efficiency method with a storage efficiency factor of 2% and a storage efficiency factor of 1%. This has been carried out for both storage and daughter units. For the Hydrocarbon daughter units the capacity has been calculated using the alternative method for hydrocarbon field storage capacity (method 2) detailed in section 4.2.1.2. It should be noted that there is also a table that details how many of the storage / daughter units it was possible to carry out this standard calculation for based on the data currently available in the database. For some countries the only available storage capacity estimates are those entered by the project partner and no standard calculation can be carried out without the use of default values in some attributes.



## 9 CONCLUSIONS

The calculations made in CO2StoP from the current project database of CO<sub>2</sub> storage locations throughout Europe paint a broad picture, but also identify the gaps in our knowledge that must be filled by further data entry, and, potentially, new geological studies, seismic surveys and drilling to make more precise data available.

It is critically important to understand the assumptions that lie at the basis of the storage capacity estimates entered in the database. These are especially relevant for saline formations, the capacities of which were derived without taking into account regulatory or economic limitations.

The CO2StoP methodology has made a significant step in progress towards establishing probabilistic estimates of the CO<sub>2</sub> storage resource in Europe in a way that will allow comparisons with other regions of the world to be made, and which will also be useful to policy makers. However, the partial data entry into the project database does make clear that the current project marks the beginning of the process of resource estimation, and certainly not the end.

## 10 ACKNOWLEDGEMENTS

We express sincere thanks to Andrei Bocin (European Commission, Joint Research Center), to Kai Tullius, Øivind Vessia, Rakel Hunstad and Ilinca Blanca (European Commission, Directorate General for Energy) for their help and support with this project and to this report and the other deliverables.

## 11 RECOMMENDATIONS

**It is recommended that:**

1. Further resources should be targeted on improving the quality and quantity of the data entered into the database, such that all three subsets of the CO<sub>2</sub> storage resource can be estimated for all countries. This is necessary in order to delineate the resource to a satisfactory level.
2. A method to estimate the dynamic<sup>7</sup> capacity of aquifers should be developed and added to the calculation engine. Additional data fields should be added to the database entry form if appropriate.
3. A cost model should be developed so that storage cost curves for various fractions of the resource can be produced.

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<sup>7</sup> The rate at which CO<sub>2</sub> can be injected into a reservoir rock



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## APPENDIX A PARTICIPANTS IN CO2STOP

Short name	Participant	Country	Participant
<b>Consortium partner</b>			
GEUS	Geological Survey of Denmark and Greenland	Denmark	Niels Poulsen
TNO-NITG	Geological Survey of the Netherlands	Netherlands	Filip Neele
BGS	British Geological Survey	UK	Sam Holloway, Karen Kirk, Nichola Smith
<b>Subcontracting partners</b>			
GBA	Geologische Bundesanstalt Austria	Austria	Gregor Goetzl
RBINS-GSB	GSB - Geological Survey of Belgium	Belgium	Kris Piessens, Kris Welkenhuysen
US	Sofia University "St. Kliment Ohridski"	Bulgaria	Georgi Geogiev
UNIZG-RGNF	University of Zagreb - Faculty of Mining, Geology and Petroleum Engineering	Croatia	Bruno Saftic, Iva Kolenkovic
CGS	Czech Geological Survey	Czech Republic	Vít Hladík
TTUGI	Institute of Geology at Tallinn University of Technology	Estonia	Alla Shogenova, Kazbulat Shogenov
BRGM	Bureau de Recherches Géologiques et Minières	France	Aurélien Leynet
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe	Germany	Stephan Knopf, Franz May
IGME (G)	Institute of Geology and Mineral Exploration	Greece	Arvantitis Apostolos
ELGI	Eötvös Loránd Geophysical Institute of Hungary	Hungary	Gyorgi Falus
GSI	Geological Survey of Ireland	Ireland	Brian McConnell
OGS	Istituto Nazionale di Oceanografia e di Geofisica Sperimentale	Italy	Giuliana Rossi, Federica Donda, Michela Vellico
GTC	Institute of Geology & Geography (Gamtos Tyrimu Centras)	Lithuania	Saulius Šliaupa
IZIIS	Institute of Earthquake Engineering and Engineering Seismology	Macedonia (FYROM)	Gavril Mirakovski
NPD	Norwegian Petroleum Directorate	Norway	Eva Halland, Wenche Tjelta Johansen
MEERI	Mineral and Energy Economy Research Institute - Polish Academy of Sciences	Poland	Radoslaw Tarkowski, K. Lubon
LNEG	Laboratório Nacional de Energia e Geologia	Portugal	Dulce Boavida
GeoEcoMar	National Institute of Marine Geology and Geo-ecology	Romania	Constantin Stefan Sava, Alexandra Dudu, Sorin Anghel
AGES	Association of Geophysicists and Environmentalists of Serbia	Serbia	Snezana Komatina-Petrovic, Sasa Smiljanic
SGUDS	Dionýz Štúr State Geological Institute	Slovakia	Dr. Ludovít Kucharič
GEO-INZ	GEOINŽENIRING d.o.o.	Slovenia	Marjeta Car
GeoZS	Geological Survey of Slovenia	Slovenia	Marko Komac, Miloš Markič, Andrej Lapanje
IGME	Instituto Geológico y Minero de Espana	Spain	Roberto Martínez Orío
ETH	ETH Zurich	Switzerland	Marco Mazzotti



## APPENDIX B DATABASE ATTRIBUTES

### Formation Attributes

Name of Attribute	Type	Size	Description
OBJECTID	Long Integer	4	Required for ArcGIS
FORMATION_ID	Text	255	Unique ID of the formation (generated by Access)
FORMATION_NAME	Text	254	Name of the Formation
ASSESS_UNIT_TYPE	Text	255	Assessment Unit type -options are saline Aquifer with or without hydrocarbon fields
PERIOD_MIN	Text	255	Minimum period of formation (select from list)
PERIOD_MAX	Text	255	Maximum period of formation (select from list)
AGE_MIN	Text	255	Minimum age of formation (select from list)
AGE_MAX	Text	255	Maximum age of formation (select from list)
STRAT_GROUP	Text	254	Stratigraphic Unit Group
STRAT_FORMATION	Text	255	Stratigraphic Unit formation
LITHOLOGY	Text	254	predominant lithology (select from list)
GEOGRAPHIC_AREA	Text	255	(select from list)
GEOLOGICAL_BASIN	Text	255	(select from list)
ON_OFFSHOR	Text	254	Whether onshore or offshore or both(Dictionary)
WATER_DEPTH	Long Integer	4	Mean average water depth
SEAL	Text	255	name of most widespread primary seal for the reservoir formation
REP_THICK	Long Integer	4	Representative thickness
REP_POR	Long Integer	4	Representative Porosity
REMARKS	REMARKS	254	Any other relevant information
STORE_CAP_FORM	Long Integer	4	Storage capacity of whole formation
STORE_CAP_HC_FIELDS	Long Integer	4	Storage Capacity of HC fields if present (populated by database)
STORE_CAP_AQUIF	Long Integer	4	Storage capacity of whole aquifer (populated by database)
COUNTRY	Text	254	
COUNTRYCODE	Text	50	
LAMBERT_E	Double	8	Eastings in Lambert projection
LAMBERT_N	Double	8	Northings in Lambert projection
X_DD	Double	8	X co-ord in decimal degrees (WGS84)
Y_DD	Double	8	y co-ord in decimal degrees (WGS84)
X	Double	8	X co-ords in any given projection
Y	Y	8	y co-ords in any given projection
Projection_Info	Text	50	Details of projection used for X and Y cords
Date_Entered	Date/Time	8	Date the data was entered



**Storage Unit Attributes**

Name	Type	Size	Description
OBJECTID	Long Integer	4	
FORMATION_ID	Text	255	Foreign key - Unique ID of the formation
STORAGE_UNIT_ID	Text	255	Unique storage unit id
STORAGE_UNIT_NAME	Text	254	Name of the storage unit
ASSESS_UNIT_TYPE	Text	255	Query - needed at this level ?Assessment Unit type -options are saline Aquifer with or without hydrocarbon fields
PERIOD_MIN	Text	255	Minimum period of formation (select from list)
PERIOD_MAX	Text	255	Maximum period of formation (select from list)
AGE_MIN	Text	255	Minimum age of formation (select from list)
AGE_MAX	Text	255	Maximum age of formation (select from list)
LITHOLOGY	Text	254	predominant lithology (select from list)
WATER_DEPTH	Long Integer	4	Mean average water depth
SEAL	Text	255	Name of most widespread primary seal for the storage unit
SUBSURF_INTERF	Text	255	Interference with other uses of subsurface (yes/no)
SURF_ISSUES	Text	255	Any surface issues (drop down selection list)
EST_STORECAP_MIN	Double	8	Minimum estimated CO <sub>2</sub> storage capacity (Mt)
EST_STORECAP_MEAN	Double	8	Mean estimated CO <sub>2</sub> storage capacity (Mt)
EST_STORECAP_MAX	Double	8	Maximum estimated CO <sub>2</sub> storage c capacity (Mt)
CAP_EST_METHOD	Text	255	Method used to estimate the storage capacity
AREAL_NET_SAND_MIN	Double	8	Minimum areal net sand (%)
AREAL_NET_SAND_MEAN	Double	8	Mean areal net sand (%)
AREAL_NET_SAND_MAX	Double	8	Maximum areal net sand (%)
GROSS_THICK_MIN	Double	8	Minimum Height / thickness of the reservoir (m)
GROSS_THICK_MEAN	Double	8	Mean Height / thickness of the reservoir (m)
GROSS_THICK_MAX	Double	8	Maximum Height / thickness of the reservoir (m)
DEPTH_MIN	Double	8	Minimum Depth (m)
DEPTH_MEAN	Double	4	Mean Depth (m)
DEPTH_MAX	Double	8	Maximum Depth (m)
PRESSURE_MIN	Double	8	Minimum Current Pressure of reservoir (bar)
PRESSURE_MEAN	Double	8	Mean Current Pressure of reservoir (bar)
PRESSURE_MAX	Double	8	Maximum Current Pressure of reservoir (bar)



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Name	Type	Size	Description
MAX_PRESSURE_MIN	Double	8	Minimum Maximum allowable pressure of reservoir after CO <sub>2</sub> injection (bar)
MAX_PRESSURE_MEAN	Double	8	Mean Maximum allowable pressure of reservoir after CO <sub>2</sub> injection (bar)
MAX_PRESSURE_MAX	Double	8	Maximum Maximum allowable pressure of reservoir after CO <sub>2</sub> injection(bar)
TEMP_C_MIN	Double	8	Minimum Temperature (c)
TEMP_C_MEAN	Double	8	Mean temperature (c)
TEMP_C_MAX	Double	8	Maximum temperature (c)
PERM_MIN	Double	8	Minimum effective permeability mD
PERM_MEAN	Double	8	Mean effective permeability mD
PERM_MAX	Double	8	Maximum effective permeability mD
POROSITY_MIN	Double	8	Minimum porosity % (old Default = 20)
POROSITY_MEAN	Double	8	Mean porosity %
POROSITY_MAX	Double	8	Maximum porosity %
FIELD_EXTENT_MIN	Double	8	Minimum Areal Extent of the storage Unit (km <sup>2</sup> )
FIELD_EXTENT_MEAN	Double	8	Mean Areal Extent of the storage Unit (km <sup>2</sup> )
FIELD_EXTENT_MAX	Double	8	Maximum Areal Extent of the storage Unit (km <sup>2</sup> )
VERT_NET_GROSS_MIN	Double	8	Minimum vertical net:gross (%)
VERT_NET_GROSS_MEAN	Double	8	Mean vertical net:gross (%)
VERT_NET_GROSS_MAX	Double	8	Maximum vertical net:gross (%)
COMPROCK_MIN	Double	8	Rock compressibility (1/Pa)
SALINITY_BRINE	Double	8	Total dissolved solids (g/l)
STATUS	Text	254	Status i.e. producing, not producing etc
STORE_EFF_FACT	Double	8	Storage efficiency factor (%)
EST_INJECT_RATE	Double	8	Estimated Injection rate, assuming single well (MtCO <sub>2</sub> /yr)
EST_PLAT_INJECT_RATE_DUR	Double	8	Estimated plateau injection rate duration(years)
INJECT_RATE_METH	Text	255	Method used to derive injection rate (drop down list)
TOT_PORE_VOL_MIN	Double	8	Minimum Total Pore Volume (m <sup>3</sup> )
TOT_PORE_VOL_MEAN	Double	8	Mean Total Pore Volume (m <sup>3</sup> )
TOT_PORE_VOL_MAX	Double	8	Maximum Total Pore Volume (m <sup>3</sup> )
EST_EFFECT_DARCY_MIN	Double	8	Minimum Estimate of effective Darcy metres (Darcy metres)
EST_EFFECT_DARCY_MEAN	Double	8	Mean Estimate of effective Darcy metres (Darcy metres)
EST_EFFECT_DARCY_MAX	Double	8	Maximum Estimate of effective Darcy metres (Darcy metres)
EST_INJECT_RATE_50_MIN	Text	255	Min Estimate of the injection rate that can be maintained for 50 years



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Name	Type	Size	Description
EST_INJECT_RATE_50_MEAN	Text	255	Mean Estimate of the injection rate that can be maintained for 50 years
EST_INJECT_RATE_50_MAX	Text	255	Max Estimate of the injection rate that can be maintained for 50 years
STORE_CAP_MIN	Double	8	Min Storage capacity - calculated by Monte Carlo ??
STORE_CAP_MEAN	Double	8	Mean Storage capacity - calculated by Monte Carlo ??
STORE_CAP_MAX	Double	8	Max Storage capacity - calculated by Monte Carlo ??
STORE_CAP_DAUGHTER	Double	8	Total Storage capacity of the daughter units
PRIM_SEAL_OVERLIE	Text	255	Does primary seal directly overlie assessment unit (yes/no)
SEAL_CHEM_REACT	Text	255	estimate of primary seal reactivity in the presence of CO <sub>2</sub> and water
MIN_SEAL_THICK	Double	8	Minimum primary seal thickness (m)
EST_CAP_ENT_PRESS	Double	8	Estimated capillary entry pressure of CO <sub>2</sub> in primary seal
FAULT_DEN	Double	8	Number of faults that cut top reservoir
VERT_EXTENT_FAULT	Double	8	Number of faults that cut the top reservoir and top seal
AVE_FAULT_THR	Double	8	Average fault throw (m)
MAX_FAULT_THR_RES	Double	8	Max fault throw at top reservoir (m)
RISK_LAT_MIGR	Text	255	Risk of lateral migration out of unit of assessment (low/medium/high)
AVE_DIP_UNIT	Double	8	Average dip of unit of assessment (degrees)
SUSCEPT_RES_DAM	Text	255	Susceptibility of reservoir to formation damage in presence of CO <sub>2</sub> (low/medium/high)
RES_MIN	Text	255	mineralogy of the reservoir
VERT_STRAT_COMPART	Text	255	Vertical reservoir compartmentalisation
HOR_STRAT_COMPART	Text	255	Horizontal reservoir compartmentalisation
FAULT_COMPART	Text	255	Fault compartmentalisation
ADVERSE_DIAG	Text	255	Risk of adverse diagenesis
SEAL_OTHER	Text	255	Secondary or other seal names
NO_WELLS_PENETR	Double	8	Number of existing wells penetrating the storage unit
WELL_VINT	Text	255	Well vintage
NO_ADAND_WELL_PENETR	Double	8	Number of abandoned wells penetrating storage unit
AGE_OLD_WELL	Double	8	Age of oldest abandoned well
VINT_PLAT	Text	255	Vintage production platform or site
SEISMIC	Text	255	Seismic available (drop down list)
WELLS	Text	255	Wells available (drop down list)
MODELS	Text	255	Models available (drop down list)
STATUS_RESEARCH	Text	255	Status of the research on the unit (drop down list)





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Name	Type	Size	Description
AVE_FAU_THR_AVE_SEAL_THI	Text	255	Average fault throw : average seal thickness
REMARKS	Text	254	
COUNTRY	Text	254	
COUNTRYCODE	Text	50	
LAMBERT_E	Double	8	Eastings in Lambert projection
LAMBERT_N	Double	8	Northings in Lambert projection
X_DD	Double	8	X co-ord of centre of storage unit (WGS84)
Y_DD	Double	8	Y co-ord of centre of storage unit (WGS84)
X	Double	8	X co-ords in any given projection
Y	Double	8	Y co-ords in any given projection
Projection Info	Text	50	Details of projection used for X and Y co-ords
Date Entered	Date/Time	8	Date the data was entered

### Daughter Unit Attributes

Attribute Name	Type	Size	Description
OBJECTID	Long Integer	4	
STORAGE_UNIT_ID	Text	255	Foreign key - Unique ID of the storage unit
TRAP_ID	Text	255	Unique id of the trap
STORAGE_UNIT_NAME	Text	254	Name of the trap
ASSESS_UNIT_TYPE	Text	255	Query - needed at this level ?Assessment Unit type -options are saline Aquifer with or without hydrocarbon fields
PERIOD_MIN	Text	255	Minimum period of formation (select from list)
PERIOD_MAX	Text	255	Maximum period of formation (select from list)
AGE_MIN	Text	255	Minimum age of formation (select from list)
AGE_MAX	Text	255	Maximum age of formation (select from list)
LITHOLOGY	Text	254	predominant lithology (select from list)
WATER_DEPTH	Long Integer	4	Mean average water depth
SEAL	Text	255	Name of most widespread primary seal for the storage unit
SUBSURF_INTERF	Text	255	Interference with other uses of subsurface (yes/no)
SURF_ISSUES	Text	255	Any surface issues (drop down selection list)
EST_STORECAP_MIN	Double	8	Minimum estimated CO <sub>2</sub> storage capacity (Mt) – aquifer daughter unit only
EST_STORECAP_MEAN	Double	8	Mean estimated CO <sub>2</sub> storage capacity (Mt) – aquifer daughter unit only



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Attribute Name	Type	Size	Description
EST_STORECAP_MAX	Double	8	Maximum estimated CO <sub>2</sub> storage capacity (Mt) – aquifer daughter unit only
CAP_EST_METHOD	Text	255	Method used to estimate the storage capacity
AREAL_NET_SAND_MIN	Double	8	Minimum areal net sand (%)
AREAL_NET_SAND_MEAN	Double	8	Mean areal net sand (%)
AREAL_NET_SAND_MAX	Double	8	Maximum areal net sand (%)
GROSS_THICK_MIN	Double	8	Minimum Height / thickness of the reservoir (m)
GROSS_THICK_MEAN	Double	8	Mean Height / thickness of the reservoir (m)
GROSS_THICK_MAX	Double	8	Maximum Height / thickness of the reservoir (m)
DEPTH_MIN	Double	8	Minimum Depth (m)
DEPTH_MEAN	Double	4	Mean Depth (m)
DEPTH_MAX	Double	8	Maximum Depth (m)
PRESSURE_MIN	Double	8	Minimum Current Pressure of reservoir (bar)
PRESSURE_MEAN	Double	8	Mean Current Pressure of reservoir (bar)
PRESSURE_MAX	Double	8	Maximum Current Pressure of reservoir (bar)
MAX_PRESSURE_MIN	Double	8	Minimum Maximum allowable pressure of reservoir after CO <sub>2</sub> injection (bar)
MAX_PRESSURE_MEAN	Double	8	Mean Maximum allowable pressure of reservoir after CO <sub>2</sub> injection (bar)
MAX_PRESSURE_MAX	Double	8	Maximum Maximum allowable pressure of reservoir after CO <sub>2</sub> injection(bar)
TEMP_C_MIN	Double	8	Minimum Temperature (c)
TEMP_C_MEAN	Double	8	Mean temperature (c)
TEMP_C_MAX	Double	8	Maximum temperature (c)
PERM_MIN	Double	8	Minimum effective permeability mD
PERM_MEAN	Double	8	Mean effective permeability mD
PERM_MAX	Double	8	Maximum effective permeability mD
POROSITY_MIN	Double	8	Minimum porosity % (old Default = 20)
POROSITY_MEAN	Double	8	Mean porosity %
POROSITY_MAX	Double	8	Maximum porosity %
FIELD_EXTENT_MIN	Double	8	Minimum Areal Extent of the storage Unit (km <sup>2</sup> )
FIELD_EXTENT_MEAN	Double	8	Mean Areal Extent of the storage Unit (km <sup>2</sup> )
FIELD_EXTENT_MAX	Double	8	Maximum Areal Extent of the storage Unit (km <sup>2</sup> )
VERT_NET_GROSS_MIN	Double	8	Minimum vertical net:gross (%)
VERT_NET_GROSS_MEAN	Double	8	Mean vertical net:gross (%)
VERT_NET_GROSS_MAX	Double	8	Maximum vertical net:gross (%)



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Attribute Name	Type	Size	Description
COMPROCK_MIN	Double	8	Rock compressibility (1/Pa)
SALINITY_BRINE	Double	8	Total dissolved solids (g/l)
STATUS	Text	254	Status i.e. producing, not producing etc - HC daughter units only
CONNECTIVITY	Text	255	Connectivity to rest of storage unit (yes / no) - aquifer daughter unit only
MIN_UR_GAS	Double	8	Minimum ultimate recovery gas (bcm - billion m3) - HC daughter units only
MEAN_UR_GAS	Double	8	Mean ultimate recovery gas (bcm - billion m3) - HC daughter units only
MAX_UR_GAS	Double	8	Maximum ultimate recovery gas (bcm - billion m3) - HC daughter units only
MIN_UR_OIL	Double	8	Minimum ultimate recover oil (MMcm) - HC daughter units only
MEAN_UR_OIL	Double	8	Mean ultimate recover oil (MMcm) - HC daughter units only
MAX_UR_OIL	Double	8	Maximum ultimate recovery oil (MMcm) - HC daughter units only
FVF_OIL	Double	8	Oil Formation Volume Factor (Rcm / scm) - HC daughter units only
FVF_GAS	Double	8	Gas Formation Volume Factor (Rcm / scm) - HC daughter units only
MIN_EST_STORE_CAP_GAS	Double	8	Min Estimated storage capacity - gas - HC daughter units only
MEAN_EST_STORE_CAP_GAS	Double	8	Mean Estimated storage capacity - gas - HC daughter units only
MAX_EST_STORE_CAP_GAS	Double	8	Max Estimated storage capacity - gas - HC daughter units only
MIN_EST_STORE_CAP_OIL	Double	8	Min Estimated storage capacity - oil - HC daughter units only
MEAN_EST_STORE_CAP_OIL	Double	8	Mean Estimated storage capacity - oil - HC daughter units only
MAX_EST_STORE_CAP_OIL	Double	8	Max Estimated storage capacity - oil - HC daughter units only
DISCOV_YR	Double	8	Discovery year - HC daughter units only
FIRST_YR_PROD	Double	8	First year of production - HC daughter units only
LAST_YR_PROD	Double	8	Last year of production - HC daughter units only
STORE_EFF_FACT	Double	8	Storage efficiency factor (%)
EST_INJECT_RATE	Double	8	Estimated Injection rate, assuming single well (MtCO <sub>2</sub> /yr)
EST_PLAT_INJECT_RATE_DUR	Double	8	Estimated plateau injection rate duration(years)
INJECT_RATE_METH	Text	255	Method used to derive injection rate (drop down list)
TOT_PORE_VOL_MIN	Double	8	Minimum Total Pore Volume (m3)
TOT_PORE_VOL_MEAN	Double	8	Mean Total Pore Volume (m3)
TOT_PORE_VOL_MAX	Double	8	Maximum Total Pore Volume (m3)
EST_EFFECT_DARCY_MIN	Double	8	Minimum Estimate of effective Darcy metres (Darcy metres)
EST_EFFECT_DARCY_MEAN	Double	8	Mean Estimate of effective Darcy metres (Darcy metres)
EST_EFFECT_DARCY_MAX	Double	8	Maximum Estimate of effective Darcy metres (Darcy metres)
EST_INJECT_RATE_50_MIN	Text	255	Min Estimate of the injection rate that can be maintained for 50 years



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Attribute Name	Type	Size	Description
EST_INJECT_RATE_50_MEAN	Text	255	Mean Estimate of the injection rate that can be maintained for 50 years
EST_INJECT_RATE_50_MAX	Text	255	Max Estimate of the injection rate that can be maintained for 50 years
STORE_CAP_MIN	Double	8	Min Storage capacity - calculated by Monte Carlo ??
STORE_CAP_MEAN	Double	8	Mean Storage capacity - calculated by Monte Carlo ??
STORE_CAP_MAX	Double	8	Max Storage capacity - calculated by Monte Carlo ??
STORE_CAP_DAUGHTER	Double	8	Total Storage capacity of the daughter units
PRIM_SEAL_OVERLIE	Text	255	Does primary seal directly overlie assessment unit (yes/no)
SEAL_CHEM_REACT	Text	255	estimate of primary seal reactivity in the presence of CO <sub>2</sub> and water
MIN_SEAL_THICK	Double	8	Minimum primary seal thickness (m)
EST_CAP_ENT_PRESS	Double	8	Estimated capillary entry pressure of CO <sub>2</sub> in primary seal
FAULT_DEN	Double	8	Number of faults that cut top reservoir
VERT_EXTENT_FAULT	Double	8	Number of faults that cut the top reservoir and top seal
AVE_FAULT_THR	Double	8	Average fault throw (m)
MAX_FAULT_THR_RES	Double	8	Max fault throw at top reservoir (m)
RISK_LAT_MIGR	Text	255	Risk of lateral migration out of unit of assessment (low/medium/high)
AVE_DIP_UNIT	Double	8	Average dip of unit of assessment (degrees)
SUSCEPT_RES_DAM	Text	255	Susceptibility of reservoir to formation damage in presence of CO <sub>2</sub> (low/medium/high)
RES_MIN	Text	255	mineralogy of the reservoir
VERT_STRAT_COMPART	Text	255	Vertical reservoir compartmentalisation
HOR_STRAT_COMPART	Text	255	Horizontal reservoir compartmentalisation
FAULT_COMPART	Text	255	Fault compartmentalisation
ADVERSE_DIAG	Text	255	Risk of adverse diagenesis
SEAL_OTHER	Text	255	Secondary or other seal names
NO_WELLS_PENETR	Double	8	Number of existing wells penetrating the storage unit
WELL_VINT	Text	255	Well vintage
NO_ADAND_WELL_PENETR	Double	8	Number of abandoned wells penetrating storage unit
AGE_OLD_WELL	Double	8	Age of oldest abandoned well
VINT_PLAT	Text	255	Vintage production platform or site
SEISMIC	Text	255	Seismic available (drop down list)
WELLS	Text	255	Wells available (drop down list)
MODELS	Text	255	Models available (drop down list)
STATUS_RESEARCH	Text	255	Status of the research on the unit (drop down list)



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<b>Attribute Name</b>	<b>Type</b>	<b>Size</b>	<b>Description</b>
AVE_FAU_THR_AVE_SEAL_THI	Text	255	Average fault throw : average seal thickness
REMARKS	Text	254	
COUNTRY	Text	254	
COUNTRYCODE	Text	50	
LAMBERT_E	Double	8	Eastings in Lambert projection
LAMBERT_N	Double	8	Northings in Lambert projection
X_DD	Double	8	X co-ord of centre of storage unit (WGS84)
Y_DD	Double	8	Y co-ord of centre of storage unit (WGS84)
X	Double	8	X co-ords in any given projection
Y	Double	8	Y co-ords in any given projection
Projection Info	Text	50	Details of projection used for X and Y co-ords
Date Entered	Date/Time	8	Date the data was entered



## APPENDIX C BLANK DATA CHECKING SHEET

### Country – Formations

1. Blank Entries?	
2. All Unique id's present?	
3. Formations Names assigned?	
4. X & Y coordinates present?	
5. Projection details for X & Ys provided?	
6. Location Check – does the value in the onshore / offshore parameter seem valid? Do the coordinates result in the data plotting in the correct country?	
7. Count for storage units matches with actual number of units for each formation?	
8. Assessment type matches between Formation, Storage and Daughter units?	
9. Country parameter populated OK?	
10. Required data populated?	

**Notes:**

### Storage Units

1. Blank Entries?	
2. All Unique id's present?	
3. All Foreign Key ids present?	
4. Storage Unit Names assigned?	
5. X & Y coordinates present?	
6. Projection details for X & Ys provided?	
7. Location check - Does data plot in correct country?	
8. Count for daughter units matches with actual number of units for each storage unit?	
9. Assessment type matches between Storage and Daughter units?	
10. Required data populated	
11. Do storage capacities for user entered and database calc appear similar?	
12. Does user want default rock and fluid compressibility values added?	

**Notes:**



**Daughter Units**

1. Blank Entries?	
2. All Unique id's present?	
3. All Foreign Key ids present?	
4. Daughter Unit Names assigned?	
5. X & Y coordinates present?	
6. Projection details for X & Ys provided?	
7. Location check - Does data plot in correct country?	
8. Count for daughter units matches with actual number of units for each storage unit?	
9. Required data populated	
10. Do storage capacities for user entered and database calc appear similar?	
11. Does user want default rock and fluid compressibility values added?	

**Notes:**

**Polygons**

1. Polygons provided	
2. Projection provided	
3. Locations check – do they plot in the correct country	
4. Do the data points plot in the correct polygons	
5. Polygons contain unique id's of the formation, storage unit. Daughter unit they relate to?	
6. Does number of polygons match number of formations	
7. Does number of polygons match number of storage units	
8. Does number of polygons match number of daughter units	



**APPENDIX D TABLE 2 – TABLE 11**

**Aquifer Storage Units**

<b>COUNTRY</b>	<b>Number storage units</b>	<b>User Estimate Store Cap Min</b>	<b>User Estimate Store Cap Mean</b>	<b>User Estimate Store Cap Max</b>
<b>Austria</b>	6	0	19600	0
<b>Belgium</b>	7	86	242	2414
<b>Bulgaria</b>	11	2270	2570	3020
<b>Croatia</b>	14	0	4070	0
<b>Czech Republic</b>	6	383	423	462
<b>Denmark</b>	4	12300	464000	3260000
<b>France</b>	5	0	29100	0
<b>Germany</b>	25	0	0	0
<b>Greece</b>	3	1860	1970	2080
<b>Hungary</b>	16	0	311	0
<b>Ireland</b>	9	0	499.9	0
<b>Italy</b>	26	4590	4590	4590
<b>Latvia</b>	1	1420	13600	46300
<b>Lithuania</b>	1	73	78	85
<b>Macedonia, The Former Yugoslav Republic Of</b>	3	20.9	20.9	20.9
<b>Netherlands</b>	18	0	1372	0
<b>Norway</b>	9	0	45000	0
<b>Poland</b>	4	7190	199000	3180000
<b>Portugal</b>	32	5700	845	0
<b>Romania</b>	15	21600	18000	53300
<b>Serbia and Montenegro</b>	2	0	0	0
<b>Slovakia</b>	37	2330	7400	13300
<b>Slovenia</b>	37	2.22	154	11.1
<b>Spain</b>	45	0	5930	0
<b>Switzerland</b>	4	0	2680	0
<b>United Kingdom</b>	96	0	0	0

Table 2: Aquifer Storage Units - User Entered CO<sub>2</sub> Storage Capacity. (Storage capacity in Mt).





<b>COUNTRY</b>	<b>Database Calc Store Cap Min</b>	<b>Database Calc Store Cap Mean</b>	<b>Database Calc Store Cap Max</b>
<b>Austria</b>	0	0	0
<b>Belgium</b>	0	227	0
<b>Bulgaria</b>	0	0	0
<b>Croatia</b>	0	4060	0
<b>Czech Republic</b>	162	448	1200
<b>Denmark</b>	263	51900	275000
<b>France</b>	0	0	0
<b>Germany</b>	0	0	0
<b>Greece</b>	4880	9500	23000
<b>Hungary</b>	0	214	0
<b>Ireland</b>	472	2050	4680
<b>Italy</b>	4590	4590	4590
<b>Latvia</b>	1420	13600	46300
<b>Lithuania</b>	49.7	84.7	132
<b>Macedonia, The Former Yugoslav Republic Of</b>	34.4	143	362
<b>Netherlands</b>	0	0	0
<b>Norway</b>	0	0	0
<b>Poland</b>	10700	198000	2950000
<b>Portugal</b>	0	0	0
<b>Romania</b>	0	0	0
<b>Serbia and Montenegro</b>	0	0	0
<b>Slovakia</b>	473	1820	5540
<b>Slovenia</b>	0	154	0
<b>Spain</b>	0	0	0
<b>Switzerland</b>	177	1850	18100
<b>United Kingdom</b>	38200	189000	547000

Table 3: Aquifer Storage Units - Database Storage Capacity Calculations carried out by the partner.  
(Storage capacity in Mt).



COUNTRY	Sum Store Cap 1percent eff Fact min	Sum Store Cap 1percent t mean	Sum Store Cap 1percent t max	Sum Store Cap 2percent t Min	Sum Store Cap 2percent t Mean	Sum Store Cap 2percent t Max
Austria	0	0	0	0	0	0
Belgium	0	164	0	0	328	0
Bulgaria	88	372	18707	175	745	37414
Croatia	0	2247	0	0	4495	0
Czech Republic	66.9	184	4951	134	367	990
Denmark	147	30300	157000	295	60700	314000
France	0	0	0	0	0	0
Germany	0	0	0	0	0	0
Greece	147	287	7090	294	574	709
Hungary	0	1810	0	0	3630	0
Ireland	210	933	20830	420	1870	??
Italy	2520	2520	2520	5040	5040	5040
Latvia	354	3390	116000	708	6780	11600
Lithuania	1140	1940	30300	2280	3890	60600
Macedonia, The Former Yugoslav Republic Of	53.9	223	5640	108	447	11300
Netherlands	0	686	0	0	1372	0
Norway	0	0	0	0	0	0
Poland	1340	25000	3310000	2680	50100	6620000
Portugal	0	0	0	0	0	0
Romania	2990	0	0	5980	0	0
Serbia and Montenegro	0	0	0	0	0	0
Slovakia	127	491	15000	255	981	30000
Slovenia	0	28.2	0	0	56.3	0
Spain	0	453	0	0	906	0
Switzerland	30.6	276	31600	61.3	553	63200
United Kingdom	18700	86500	2470000	37300	173000	4940000

Table 4: Aquifer Storage Units - Standardised CO<sub>2</sub> Storage Capacity Calculations. (Storage capacity in Mt).



<b>COUNTRY</b>	<b>Total number storage units</b>	<b>Num Units With Null Min Value</b>	<b>Num Units With Null Mean Value</b>	<b>Num Units With Null Max Value</b>
<b>Austria</b>	6	6	6	6
<b>Belgium</b>	7	7	2	7
<b>Bulgaria</b>	11	1	1	1
<b>Croatia</b>	14	14	9	14
<b>Czech Republic</b>	6	2	2	2
<b>Denmark</b>	4	0	0	0
<b>France</b>	5	5	5	5
<b>Germany</b>	25	25	25	25
<b>Greece</b>	3	0	0	0
<b>Hungary</b>	16	16	9	16
<b>Ireland</b>	9	8	0	8
<b>Italy</b>	26	12	12	12
<b>Latvia</b>	1	0	0	0
<b>Lithuania</b>	1	0	0	0
<b>Macedonia, The Former Yugoslav Republic Of</b>	3	0	0	0
<b>Netherlands</b>	18	18	18	18
<b>Norway</b>	9	9	9	9
<b>Poland</b>	4	0	0	0
<b>Portugal</b>	32	32	32	32
<b>Romania</b>	15	1	15	15
<b>Serbia and Montenegro</b>	2	2	2	2
<b>Slovakia</b>	37	1	0	1
<b>Slovenia</b>	37	37	0	37
<b>Spain</b>	45	45	1	45
<b>Switzerland</b>	4	0	0	0
<b>United Kingdom</b>	96	22	16	22

Table 5: Aquifer Storage Units - Number of Storage Units where it was not possible to recalculate the storage capacity. (Storage capacity in Mt).



**Aquifer Daughter Units**

<b>COUNTRY</b>	<b>Number Aquifer Daughte rs</b>	<b>User Calc Min Stora ge</b>	<b>User Calc Mean Stora ge</b>	<b>User Calc Max Stora ge</b>	<b>Databa se Calc Min Storage</b>	<b>Databa se Calc Mean Storage</b>	<b>Databa se Calc Max Storage</b>
<b>Belgium</b>	2	15	27	40	0	0.38	0
<b>Czech Republic</b>	4	167	188.4	210	66	219	616
<b>Denmark</b>	10	15730	16027	17000	19900	23200	29500
<b>France</b>	5	0	0	0	0	0	0
<b>Germany</b>	24	1102	0	2887	0	0	0
<b>Greece</b>	5	1876	1976	2100	6200	9720	16500
<b>Hungary</b>	5	0	450.2	0	0	318	0
<b>Ireland</b>	1	0	40.5	0	0	0	0
<b>Latvia</b>	18	337	919	929	0	347	0
<b>Lithuania</b>	2	68	72.7	80	146	146	146
<b>Macedonia, The Former Yugoslav Republic Of</b>	17	130.7	130.7	130.7	14.9	44.9	84.5
<b>Netherlands</b>	5	100	1372.5	225	0	0	0
<b>Norway</b>	3	0	391	0	0	0	0
<b>Poland</b>	33	4433.6	5942.8	7076.9	4836	5943	7060

Table 6: Aquifer Daughter Units - User entered storage capacity and Database calculated storage capacity carried out by the partners. (Storage capacity in Mt).



<b>COUNTRY</b>	<b>Sum Storage Eff 1percent t Min</b>	<b>Sum storage eff 1percent t mean</b>	<b>Sum Storage Eff 1percent t Max</b>	<b>Sum Storage Eff 2percent t Min</b>	<b>Sum Storage Eff 2percent t Mean</b>	<b>Sum Storage Eff 2percent t Max</b>
<b>Belgium</b>	0	0.19	0	0	0.38	0
<b>Czech Republic</b>	6.32	20.8	58.7	12.6	41.6	117
<b>Denmark</b>	566	710	882	1130	1420	1760
<b>France</b>	0	0	0	0	0	0
<b>Germany</b>	0	0	0	0	0	0
<b>Greece</b>	192	297	500	384	594	999
<b>Hungary</b>	0	2322	0	0	4645	0
<b>Ireland</b>	0.64	1.41	2.38	1.29	2.83	4.76
<b>Latvia</b>	0	80	0	0	160	0
<b>Lithuania</b>	5.03	5.03	5.03	10.1	10.1	10.1
<b>Macedonia, The Former Yugoslav Republic Of</b>	11.7	35.3	67.3	23.3	70.6	135
<b>Netherlands</b>	0	0	0	0	0	0
<b>Norway</b>	0	0	0	0	0	0
<b>Poland</b>	456	561	668	911	1120	1340

Table 7: Standardised Aquifer Daughter Units CO<sub>2</sub> Storage Capacity Calculations. (Storage capacity in Mt).



COUNTRY	Total Number Aquifer Daughters	Num Daughter Units Null Values Min	Num Daughter Units Null Values Mean	Num Daughter Units Null Values Max
Belgium	2	2	0	2
Czech Republic	4	0	0	0
Denmark	10	0	0	0
France	5	5	5	5
Germany	24	24	24	24
Greece	5	0	0	0
Hungary	5	5	0	5
Ireland	1	0	0	0
Latvia	18	18	0	18
Lithuania	2	0	0	0
Macedonia, The Former Yugoslav Republic Of	17	0	0	0
Netherlands	5	5	5	5
Norway	3	3	3	3
Poland	33	0	0	0

Table 8: Aquifer Daughter Units - Number of Daughter Units where it was not possible to recalculate the storage capacity. (Storage capacity in Mt).

**Hydrocarbon Daughter Units**

COUNTRY	User Estimated Min Gas Store Cap	User Estimated Mean Gas Store Cap	User Estimated Max Gas Store Cap	User Estimated Min Oil Store Cap	User Estimated Mean Oil Store Cap	User Estimated Max Oil Store Cap
Austria	0	22000	0	0	17	0
Bulgaria	4	5	6	0	0	0
Croatia	0	136	0	0	38.9	0
Czech Republic	16.3	18.0	19.7	1.25	1.4	1.55
France	0	0	0	0	38.5	0
Germany	0	2255	0	0	98	0
Greece	5.5	6	6.5	29	31	34
Hungary	0	95.0	0	0	3.06	0
Ireland	0	332	0	0	0	0
Italy	133	133	133	1.06	1.06	1.06
Lithuania	0.59	0.59	0.59	6.49	6.49	6.49
Netherlands	9.8	9960	10.2	0	0	0
Romania	0	267.56	0	13	147	23
Slovakia	0.4	0.521	0.63	0.2	0.3	0.4
United Kingdom	4670	5280	5610	2430	2440	2480

Table 9: Hydrocarbon Daughter Units - User Estimated CO<sub>2</sub> Storage Capacity (Oil and Gas fields). (Storage capacity in Mt).



<b>COUNTRY</b>	<b>Database Calculated Min Store Cap Gas</b>	<b>Database Calculated Mean Store Cap Gas</b>	<b>Database Calculated Max Store Cap Gas</b>	<b>Database Calculated Min Store Cap Oil</b>	<b>Database Calculated Mean Store Cap Oil</b>	<b>Database Calculated Max Store Cap Oil</b>
<b>Austria</b>	0	0	0	0	0	0
<b>Bulgaria</b>	0	0	0	0	0	0
<b>Croatia</b>	0	0	0	0	0	0
<b>Czech Republic</b>	17.8	19.5	21.1	1.93	2.06	2.16
<b>France</b>	0	0	0	0	0	0
<b>Germany</b>	0	0	0	0	0	0
<b>Greece</b>	917	1010	1100	30.9	32.5	34.5
<b>Hungary</b>	0	87.59357393	0	0	335	0
<b>Ireland</b>	0	0	0	0	0	0
<b>Italy</b>	132	132	132	1.06	1.06	1.06
<b>Lithuania</b>	1.05	1.05	1.05	4.74	4.74	4.74
<b>Netherlands</b>	1910	2640	3380	0	0	0
<b>Romania</b>	0	0	0	0	0	0
<b>Slovakia</b>	0.054	0.063	0.072	0	0	0
<b>United Kingdom</b>	5530	6270	6710	2730	2750	2740

Table 10: Hydrocarbon Daughter Units - Standardised Storage Capacity calculations. (Storage capacity in Mt).



<b>COUNTRY</b>	<b>Total Number of Daughter Units</b>	<b>Daughter Units with no Database calc value</b>
<b>Austria</b>	2	2
<b>Bulgaria</b>	1	1
<b>Croatia</b>	17	17
<b>Czech Republic</b>	2	0
<b>France</b>	28	28
<b>Germany</b>	51	51
<b>Greece</b>	3	1
<b>Hungary</b>	14	0
<b>Ireland</b>	1	1
<b>Italy</b>	14	0
<b>Lithuania</b>	12	0
<b>Netherlands</b>	142	17
<b>Romania</b>	30	30
<b>Slovakia</b>	4	2
<b>United Kingdom</b>	192	38

Table 11: Hydrocarbon Daughter Units - Number of Daughter Units where it was not possible to recalculate the storage capacity